

N91-21591

SECTION II.

REPORT OF THE PANEL ON PLATE MOTION AND DEFORMATION

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SECTION II.

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SUMMARY

GOALS AND OBJECTIVES

Our goal is to understand the motions of the plates, the deformation along their boundaries and within their interiors, and the processes that control these tectonic phenomena. In the broadest terms, we must strive to understand the relationships of regional and local deformation to flow in the upper mantle and the rheological, thermal and density structure of the lithosphere. The essential data sets which we require to reach our goal consist of maps of current strain rates at the Earth's surface and the distribution of integrated deformation through time as recorded in the geologic record. Our success will depend on the effective synthesis of crustal kinematics with a variety of other geological and geophysical data, within a quantitative theoretical framework describing processes in the Earth's interior. Only in this way can we relate the snapshot of current motions and Earth structure provided by geodetic and geophysical data with long-term processes operating on the time scales relevant to most geological processes.

The wide-spread use of space-based techniques, coupled with traditional geological and geophysical data, promises a revolution in our understanding of the kinematics and dynamics of plate motions over a broad range of spatial and temporal scales and in a variety of geologic settings. The space-based techniques that best address problems in plate motion and deformation are precise space-geodetic positioning —on land and on the seafloor— and satellite acquisition of detailed altimetric and remote sensing data in oceanic and continental areas.

Of the overall science objectives for the NASA Solid Earth Science plan for the 1990's, our interests are most relevant to Objective #4: "Understand the motion and deformation of the lithosphere within and across plate boundaries", and are also clearly pertinent to understanding the dynamics of the mantle, the structure and evolution of the lithosphere, and the landforms that result from local and regional deformation (Objectives #2 and #3).

In order to reach our goal of understanding plate-scale tectonics and kinematics, we have identified major objectives for the development and application of space technology in the context of a NASA program for the 1990's:

1. *Refine our knowledge of plate motions:*

- Determine the variability of plate motion on time scales short compared with the averaging time of geological plate models;
- Measure the vector motion between plates with poorly determined or questionable relative velocities;
- Understand the driving mechanisms of plate tectonics.

2. *Study regional and local deformation:*

- Determine the kinematics of deformation within plate margins and interiors;
- Understand the dynamics of plate deformation along plate margins and in tectonically active intra-plate regions;
- Evaluate the non-rigid large-scale behavior of plates.

3. *Contribute to the solution of important societal problems*

- Alleviate the risks associated with various natural hazards, such as seismic and volcanic activity, and contribute to the International Decade of Natural Hazard Reduction;
- Permit direct measurements of the pattern of vertical displacement of the crust, and thus remove ambiguities inherent to the problem of eustatic sea-level changes, a critical aspect of global warming issues;
- Contribute useful constraints to the search for mineral and hydrocarbon resources.

REQUIREMENTS

In addition to basic space-positioning measurements, the pursuit of these objectives will require the use of global and regional data sets obtained with space-based techniques. These include topographic and geoid data to help characterize the internal processes that shape the planet, gravity data to study the density structure at depth and help determine the driving mechanisms for plate tectonics, and satellite images to map lithology, structure and morphology. These requirements are summarized in the following table:

Measurements	Precision required	Spatial scale/resolution
<i>Horizontal motions</i>		
Variability of plate motion	1-10 mm/yr	10^4 km
Vector motion between plates	1-10 mm/yr	$10^2 - 10^3$ km
Nonrigid plate behavior	1 mm/yr	10^3 km
Regional and local deformation	1 mm/yr	$10^1 - 10^2$ km
Post-seismic deformation	10-100 mm over hours	$10^0 - 10^2$ km
<i>Vertical motions</i>		
Post-glacial rebound	1 - 4 mm/yr	$10^3 - 10^4$ km
Active vertical tectonics	0.1 - 1 mm/yr	$10^1 - 10^3$ km
Thermal & dynamical processes	0.01 - 0.1 mm/yr	$10^2 - 10^3$ km
Continental epeirogeny	0.03 mm/yr	10^3 km
Post-seismic deformation	10-100 mm over hours	$10^0 - 10^2$ km
<i>Satellite images</i>		
Regional studies	10 - 30 m multispectral	$10^2 - 10^3$ km
Local and neotectonic studies	1 m single band	$10^0 - 10^2$ km
<i>Topography & altimetry</i>		
Global continental topography	10 m vertical	1 km
Global oceanic bathymetry	10 m vertical	20 km
Local topography	1 m vertical	10 - 100 m
<i>Gravity</i>		
Regional tectonic studies	1 - 2 mgal	50 - 100 km
Local tectonic studies	0.1 - 1 mgal	10 km
Post-glacial rebound	1 μ gal	1000 km
<i>Magnetics</i>		
Global crustal anomalies	1 nT	100 km
Local anomalies	1 nT	1 km

RECOMMENDATIONS

Basic Recommendations

Our panel has four specific recommendations:

[1] In order to study plate motion we need a global distribution of geodetic stations that measure relative positions to 1 cm over one day and to 1 mm over three months. In order to monitor regional and local deformation we need a terrestrial reference frame. Both of these objectives can be accomplished with a global distribution of space-geodetic observatories.

This can be best accomplished by:

- deploying a world-wide network of dedicated, continuously monitoring GPS stations with 1000 km spacing and measuring relative positions to 1 cm over one day and to 1 mm over three months. Approximately 150 stations will be required on the continents with another 50 stations located on islands, for a total of about 200 stations;
- deploying a full constellation of GPS satellites to support this network.
- continuing a world-wide network of approximately 12 VLBI/SLR sites with at least one on each major plate and several distributed around the Pacific Ocean. These sites must maintain relative positions to 1 cm over one day and to 1 mm over three months to determine earth orientation and GPS fiducial coordinates;
- co-locating GPS receivers at other existing VLBI/SLR stations and ceasing to occupy these stations as soon as it can be done without loss in precision and without offsets in the data series.
- continuing a network of SLR stations with positions relative to the earth's center-of-mass determined with sufficient accuracy to provide adequate orbits for the GPS satellites. At such time as GPS (or some other system) demonstrates a capability of meeting center-of-mass requirements at the same level these SLR sites will no longer be required for this purpose;

[2] In order to monitor deformation in tectonically active areas where deformation is concentrated, we need a finer spacing of geodetic sites. We recommend the initiation of a vigorous long-term program of monitoring regionally dense networks deployed across tectonically active regions, to measure and analyze motion and deformation over a broad range of spatial and temporal scales.

- Some obvious scientific problems include: the kinematics of major plate convergence systems; the distribution and rate of post-glacial rebound; and the distribution of deformation within tectonically active areas, such as western North America, the Pacific Basin, and the Alpine-Himalayan collision zone. Specific experiments should be selected through a peer-review process to ensure the highest quality of science.
- We recommend that resources be allocated among three modes of operation as follows: continuously recording arrays—45%; mobile campaigns (GPS / GLRS)—45%; Seafloor positioning campaigns—10%.

[3] We need globally coherent topography, geoid, and gravity coverage, and we need high-resolution satellite imagery and topography and gravity coverage in local areas.

These requirements are defined as:

- Global, coherent topographic data with moderately high accuracy (10 m vertical and 1 km horizontal). High resolution capability (a few meters vertical and 10 m horizontal) applied in selected areas.
- High resolution satellite images (roughly 1 m pixel size, even if only at single spectral band) for identification of structural, neotectonic and other morphologic features from space. Lower resolution (10 m) needed over a wide range of spectral bands to distinguish different lithologies.
- Globally dense, coherent gravity data to a few mgal at resolution of 50-100 km and local high-resolution gravity data to a few mgal at resolution approaching km.

[4] We require technological development to permit in a number of applications of space-based geodesy that are not possible with current capabilities.

Indispensable technology includes:

- a new generation of systems capable of continuous mm to sub-mm horizontal and vertical positioning on 1 to 1000 km vectors; systems capable of sub-cm relative positioning of moving platforms; and inexpensive (< \$10K), transportable (< 5 kg), and rugged instruments with minimal power requirements (~ 1 W);
- monumentation stable at the sub-millimeter level, and marks that can be installed rapidly and economically;
- seafloor mark positioning with a precision of better than 1 cm;
- more efficient and accurate processing techniques to reduce cost of analysis and delay in interpretation of large data sets;
- the creation and maintenance of a permanent geodetic archive for existing data sets and for those collected during the next decade, with common data formats and convenient access;
- effective, affordable, and practical means for exchange and dissemination of remote sensing data such as EosDIS or SESDIS. This effort should be coordinated with other agencies and countries.

A global fiducial network

The most important recommendation of our panel is for the implementation of a world-wide space-geodetic fiducial network to provide a systematic and uniform measure of global strain. As outlined above, we recommend that this network consist of globally distributed GPS receivers tied to a number of strategically located VLBI/SLR stations. We further recommend that some stations be equipped with an expanded set of additional sensors to facilitate calibration of various space-based data sets. These may include

gravimeters, magnetometers, environmental sensors, and calibrated targets for various orbital instruments, such as those planned for Eos. In the long term, GLRS reflectors should be co-located with the VLBI/SLR and GPS stations.

Direct scientific benefits that will accrue from the proposed network include monitoring of :

- Plate motions, especially important for plates with poorly determined vector velocities;
- Short-term variations in rates of plate motion and deformation (days to years);
- Non-rigid behavior of plate interiors (important for models of plate driving forces);
- Rates of post-glacial rebound (constrains viscosity models for the mantle);
- Rates of sea-level change (crucial for study of global warming and climate change).

Additional benefits identified by our panel include:

- Determination of highly accurate orbits for GPS and other spacecraft;
- Mission support and satellite tracking;
- Calibration of globally coherent space-based topography, gravity and magnetic data;
- Calibration of a global set of GLRS reflectors;
- Establishment of an accurate fiducial network for local and regional space-geodesy;
- Assessment of natural hazards (earthquakes and volcanoes).

The specifications listed above for the number, density and type of space-positioning stations are based on both scientific and technical considerations: we require at least three sites per major plate to resolve rigid plate motions; mapping of non-rigid behavior within the interiors of plates requires a denser distribution. For example, with a station spacing of 1000 km there will be approximately 30 sites in North America - enough to map the distribution of non-rigid behavior across the continental part of the plate. The cost of deploying this number of VLBI or SLR stations would be prohibitive. GPS provides a relatively inexpensive alternative using current technology. The required accuracy of the network is dictated by the rates of movement that we wish to determine, as described in Table 1.

In tectonically active areas where deformation is concentrated, we need geodetic stations with intersite spacing much smaller than the 1000 km provided by the permanent sites within the network. We therefore recommend a vigorous long-term program of monitoring regionally dense space-geodetic networks through periodic campaigns (every two or three years) using portable equipment. These regional networks will be intimately tied to the permanent geodetic stations. Taken together, these two components —the permanent sites and the regional densification networks— will allow us to create a global strain map of the planet. Furthermore, the permanent fiducial network will foster studies of local and regional deformation because it will provide a means of tying local observations to a global framework and will greatly simplify the computations required to do so.

One of the outstanding problems with existing topography data is their lack of global coherence. Under our proposal, we will have 200 sites distributed around the world with accurately determined absolute elevations. This will permit topographic data sets to be calibrated precisely at each of these sites and removal of any offsets in the data sets. Similarly, enhancement of a subset of the global sites with other devices (e.g. gravimeters, magnetometers, calibrated targets for orbital instruments) will provide superior calibration of a variety of other space-based observations of the earth.

In addition to its obvious scientific benefits, the proposed network will facilitate the quest for natural hazard reduction by permitting study of the phenomena that control seismic and volcanic activity. Comparisons between crustal kinematics, seismicity and other environmental data are crucial to achieve a quantitative understanding of these phenomena. Particularly noteworthy is the need to establish permanent geodetic, geophysical, and environmental facilities in areas of frequent volcanic or seismic activity, so as to acquire a continuous record of short-term behavior immediately before and after major eruptions and earthquakes and to aid in their prediction. Such facilities will also assist in the assessment of global warming through evaluation of absolute sea-level change and estimation of the rate of melting of polar ice-caps. Deployment of the proposed network in the 1990's will thus be timely in its response to the call for an increased emphasis over the next decade on the reduction of natural hazards and evaluation of man-made climate change.

Establishment and maintainance of a global network requires a long-term commitment and a global focus. While inter-agency and international participation is clearly critical to a successful deployment, it is imperative that a single agency take the initiative and the responsibility for the development and implementation. As a mission-oriented space agency with a global outlook, NASA is uniquely poised to lead this effort. As the prime developer of space geodesy, NASA is uniquely poised to tackle this technological challenge. Finally, NASA is perhaps the only agency in a position to make the necessary long-term commitment to this global program. In this light, we view deployment of a space-based geodetic network as an integral part of the *Mission to Planet Earth*.

1. INTRODUCTION

During the previous decade, the NASA program in Crustal Dynamics has been extremely successful in directly measuring instantaneous plate motions. Decadal changes in baselines over intercontinental distances using techniques such as VLBI and SLR match, in general, the values predicted from geologically-based rigid-plate motion models such as RM2 [Minster and Jordan, 1978] and NUVEL-1 [DeMets *et al.*, 1990] which average tectonic movements over 10^6 -yr time scales. This remarkable agreement between short-term motions between plates and those observed on geological time scales has motivated and justified the use of the latter as *a priori* information in the reduction and interpretation of space-geodetic data. In adopting this approach, one recognizes implicitly that the geodetic signals of interest are not plate motions in the classical sense, but the differences between geodetically-derived motions and the geologically-predicted ones. In this light, the primary impact of the NASA program for the 1990's on plate tectonics will be to permit quantitative measurements of departures from the classical geological description of horizontal and vertical motions of the major plates. Such departures fall into two major categories: 1) large scale and regional scale non-rigid behavior (plate deformation and plate boundary zones of deformation), and 2) Time-dependent motions, including post-seismic strains and aseismic deformations.

For example, in the plate tectonic hypothesis, the lithospheric plates are taken to be rigid, their speeds are assumed to remain steady for long periods of time, and their motions are described as rigid-body rotations along the surface of the Earth except at convergent and divergent plate boundaries [e.g., Le Pichon *et al.*, 1976]. However, we know that at some point these predictions must break down. Local and regional departures from rigid plate behavior occur along inter-plate boundaries and within domains of intra-plate deformation. Where deformation involves oceanic lithosphere, it is primarily localized along narrow, well-defined zones that form discrete boundaries between plates. Where plate boundary deformation involves continental lithosphere, it is commonly distributed over complex networks of faults and folds up to several thousand kilometers wide. On a geologic timescale, permanent deformation is commonly partitioned into zones of intense diastrophism along the margins of less deformed crustal fragments whose dimensions range from tens to hundreds of kilometers, and which experience different rates of horizontal and vertical motions. This spatial complexity is demonstrably tied to temporal variations in the pattern of motions. In contrast to global plate motions, the complex history of deformation within regions of plate boundary interaction and intra-plate deformation is known in most areas only at the crudest level of detail.

Many earthquakes occur in plate interiors, with focal mechanisms implying both horizontal and vertical relative motions. The earthquake recurrence time itself imposes a time-dependence to the rate of motion, at least in the vicinity of the rupture: along plate boundaries, earthquakes can reflect a significant fraction of the total relative motion, which takes place episodically. By directly observing such transients as departures from the rigid-plate model predictions we can bound the state of stress in plate interiors, constrain the short-term rheology of the lithosphere and asthenosphere [e.g. *Elsasser* 1969; *Melosh*, 1976; 1977, 1983; *Cohen*, 1984; *Rundle and Jackson*, 1977; *Rundle*, 1988a,b], and test various models of plate-driving forces. On longer time scales, subsidence of basins on the foreland side of thrust belts is known to result from loading of flexurally strong lithosphere by nappe emplacement and by forces that originate at depth within the mantle [*Lyon-Caen and Molnar*, 1985; *Royden*, 1987]. Careful analysis of the timing and magnitude of deformation allow us to constrain ideas about the processes that drive it and about the long-term mechanical behavior of the lithosphere, but the details remain poorly understood.

While the attention of our panel is focused on plate motion and deformation, the details are likely to be of great importance in understanding the driving forces and the interaction between the Earth's crust and mantle. In this respect, the goals of our panel overlap strongly with those of the "*Earth Structure and Dynamics*" and the "*Lithospheric Structure and Evolution*" panels. Likewise, many landforms, from the very local, such as fault scarps, to the regional, such as topographically high mountains, are the direct result of deformation processes, and mandate close ties to the "*Landforms and Paleoclimate*" panel and to the "*Volcanism*" panel.

2. GOAL

Our goal is to understand the motions of the plates, the deformation along their boundaries and within their interiors, and the processes that control these tectonic phenomena. In the broadest terms, we must strive to understand the relationships of regional and local deformation to flow in the upper mantle and the rheological, thermal and density structure of the lithosphere. The essential data sets which we require to reach our goal consist of maps of current strain rates at the Earth's surface and the distribution of integrated deformation through time as recorded in the geologic record. Our success will depend on the effective synthesis of crustal kinematics with a variety of other geological and geophysical data, within a quantitative theoretical framework describing processes in the Earth's interior. Only in this way can we relate the snapshot of current motions and Earth structure provided by geodetic and geophysical data with long-term processes operating on the time scales relevant to most geological processes.

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3. PANEL OBJECTIVES

In order to reach our goal of understanding plate-scale tectonics and kinematics, we have identified major objectives for the development and application of space technology in the context of a NASA program for the 1990's:

1. *Refine our knowledge of plate motions:*
 - Determine the variability of plate motion on time scales short compared with the averaging time of geological plate models;
 - Measure the vector motion between plates with poorly determined or questionable relative velocities;
 - Understand the driving mechanisms of plate tectonics.

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In addition to basic space-positioning measurements, the pursuit of these objectives will require the use of global and regional data sets obtained with space-based techniques. These include topographic and geoid data to help characterize the internal processes that shape the planet, gravity data to study the density structure at depth and help determine the driving mechanisms for plate tectonics, and satellite images to map lithology, structure and morphology.

In the remainder of this section, we elaborate on these objectives, and examine the role of space-based techniques to achieve them, in light of the current state of the art. The associated scientific requirements, in terms of resolution, accuracy, and overall capabilities, will be discussed in Section 4. We base much of the discussion below on Chapter II [Agnew *et al.*, 1989] of the Workshop on “*The Interdisciplinary Role of Space Geodesy*”, held in Erice, Sicily in July, 1988 [Mueller and Zerbini, eds, 1989, hereafter referred to as the Erice report].

3.1 Plate motions

Current geological estimates of the relative velocities between the dozen or so major rigid plates are constrained by three basic types of data collected along mainly submerged plate boundaries: (1) spreading rates on mid-ocean ridges from magnetic anomalies, and directions of relative motion from (2) transform-fault azimuths and (3) earthquake slip vectors. The first self-consistent global models were synthesized soon after the formulation of plate tectonics [Le Pichon, 1968], and significant refinements have been made since [Chase, 1978; Minster and Jordan, 1978; De Mets *et al.*, 1989]. Seafloor magnetic anomalies used to construct these rigid-plate motion models average rates over the last 2-3 million years. This interval is geologically brief, and the small plate displacements that take place during it are well described by infinitesimal (as opposed to finite) rotations. In these models, the formal uncertainties in the angular velocity components are quite small, corresponding to 1 or 2 mm/yr in the predicted rates of relative motions. More importantly, at this level the most recent model for plate motion (NUVEL-1) is consistent with the hypothesis that major plates behave rigidly over a million-year time scale.

There is now convincing evidence that the rates-of-change of geodetic baselines spanning plate boundaries are consistent with the geological estimates [e.g., Herring *et al.*, 1986], provided that the endpoints are located within stable plate interiors. This is

important as a check on the positioning techniques and corroborates the geophysical expectation that the instantaneous velocities between points in stable plate interiors are dominated by secular plate motions (Figures 1 and 2). This means that, for those plates whose motions are well constrained by geological observations, the improvement of existing models of present-day motion among the major plates requires that—for interplate baselines with endpoints located within stable plate interiors—the tangential components of relative velocities be resolved to an accuracy on the order of 1 mm/yr.

It is therefore clear that geologically-based global plate motion models provide a kinematic reference frame in which to analyze short-term geodetic observations, and the kinematic boundary conditions which must be satisfied by models of plate boundary deformation zones. The most important and interesting geodetic signals with characteristic time scales ranging from 0 to 100 years will be departures from predictions of million-year average rates based on geological rigid-plate models. The major types of such departures include non-rigid behavior within plates and along their boundaries and time-dependent (nonsteady) horizontal and vertical motions. Because they must be direct manifestations of detailed aspects of the underlying geodynamical physical processes, these are among the most exciting issues in plate tectonics to be addressed by space geodesy.

3.1.1 Recent changes in plate motions

Space-geodetic (VLBI and SLR) measurements of relative plate motions show that the geological predictions of the directions and rates of plate motion are generally well matched by direct measurements over short time scales. Any changes in plate velocities over a time span significantly shorter than the 10^6 yr would be difficult to detect and document using geological observations alone. Although space-geodetic data sets are still sparse along many baselines and show much more scatter than the geological observations used to construct the rigid-plate models, tantalizing evidence has been uncovered from VLBI that the North Atlantic—probably the best sampled boundary—may be opening at an instantaneous rate slower than predicted from the geology [e.g., *Herring*, 1988]. On the other hand, these observations may be contaminated by vertical drift at Wettzell, FRG, of as much as 10 mm/yr *T. Herring*, CDP presentation, 1989]. The same behavior is seen at the Wettzell SLR station (*Smith et al.*, 1989a). To decide whether we can truly detect changes in plate velocities by space geodesy, we must analyze many baselines crossing a variety of plate boundaries and continue to monitor a global space-geodetic network.

Given a set of interplate baselines connecting the major plates and monitored regularly over a sufficiently long period of time, we will acquire the necessary time series to begin to address the following first order questions, beyond the mere comparison between the geodetic and geologic rates (both globally and locally):

On what time scales are plate motions steady? Is there a global pattern to time dependence? How does this relate to what is occurring on the boundaries of those plates? Is there a correlation with “absolute” motions or hot spot activity?

How is the variability of motion along the strike of plate boundaries related to the variability across and away from the boundary? How does this impact our ideas concerning the physical mechanisms governing plate motions?

We must also note that such observations will affect the definition of global geodetic reference frames. In order to answer such questions, we must pursue a systematic and coordinated program to measure the relative motions of the interiors of major plates using space geodesy. This endeavor requires a global network, and care must be taken to insure continuity and uniformity of the data over decadal time spans, starting with the ongoing programs.

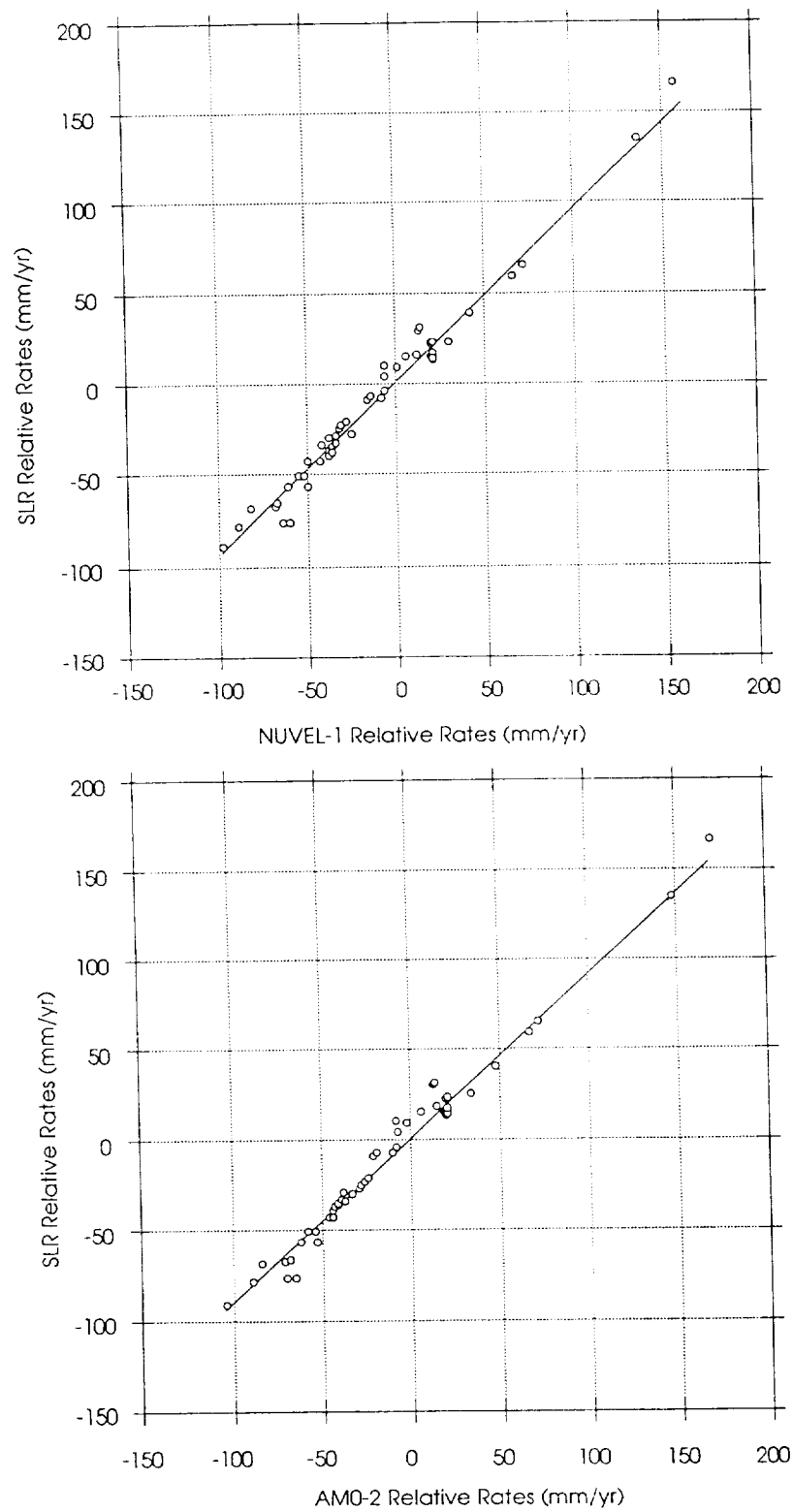


Figure 1. Comparison of observed instantaneous rates of plate motion from changes in baseline length monitored by satellite laser ranging (open circles) with those predicted by two geologic models: NUVEL-1 (upper panel) and AM0-2 (lower panel). In the top frame, the slope of the line is 0.949 ± 0.019 , and in the bottom frame, it is 0.914 ± 0.017 , indicating close agreement, although the space-geodetic rates are 3% to 7% slower than the geological estimates. (From *Smith et al* [1990]).

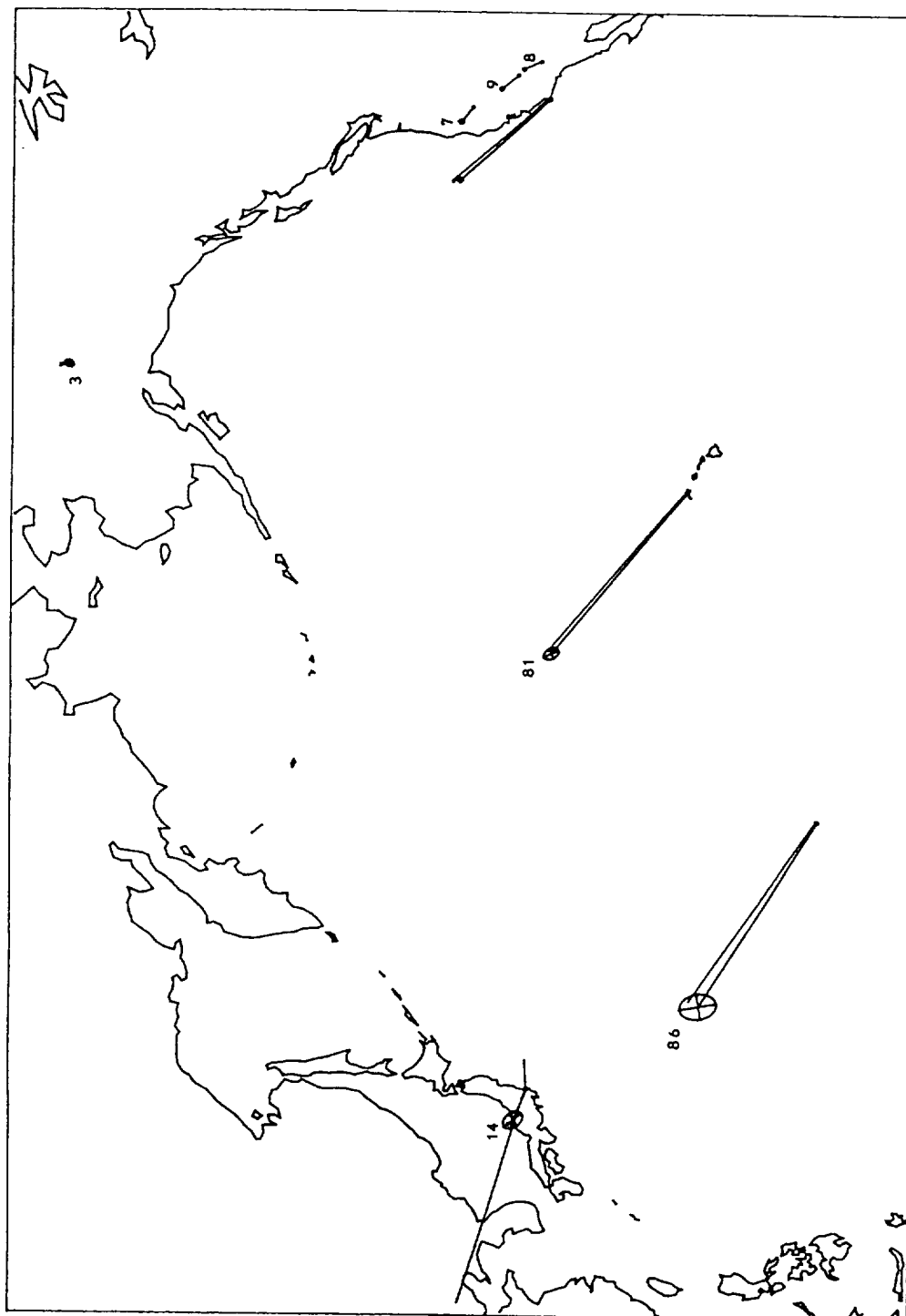


Figure 2. Comparison of vector rates and directions of absolute plate motions determined from geology with the observed instantaneous vector velocities from VLBI measurements (lines which terminate in uncertainty ellipses) for several sites on or bordering the Pacific plate. Note that in almost all cases, the observed vectors fall within the uncertainty ellipses determined from geologic observations. (T. Clark, 1990, personal communication.)

3.1.2 Vector motion between plates with poorly determined velocities

Velocity estimates across all consuming plate boundaries such as trenches and active mountain belts are determined mainly by geometrical inference, assuming the plates to be rigid on geological time scales. The primary geological indicators of the direction of relative motion across such boundaries consist of earthquake slip vectors, which are typically much more uncertain than other direction indicators such as transform fault azimuths, and can be contaminated by local conditions affecting the details of earthquake rupture [e.g. *Minster and Jordan*, 1978; *DeMets et al.*, 1990]. For plates with no spreading boundary, such as the Philippine plate, no reliable rates are available and slip vectors are the only indicators of the direction of motion, so that geological estimates of the motions of such plates are at best extremely uncertain, and quite possibly wrong. In some areas (e.g., SE Asia), the rigid plate model cannot be used even if it is applicable, because the plate geometry is so poorly determined.

Global space-geodetic networks, judiciously densified in such areas, and monitored over a sufficiently long period of time offer the only practical means of addressing these problems by providing direct, quantitative measurements of tectonic motions. However, it is essential to recognize from the outset that, unless we are prepared to wait for a time period long compared to the earthquake cycle, such a geodetic program must be supported by a concomitant effort aimed at improving our understanding of the recent geological and geophysical history of the region. This is a critical point, which is raised again in the context of regional and local deformations: without the supporting field and modeling studies, the interpretation of space-geodetic data in terms of long term geological phenomena will remain doubtful.

The primary focus of such applications of space geodesy in the next decade would be on plate pairs separated by trenches, such as in the western Pacific and along the Pacific coast of the Americas. In such cases, space geodesy can help refine the rigid-plate models locally and permit tests of assumptions, such as plate rigidity. In places where the geological record is difficult to obtain or interpret, such as the Philippine plate and much of the southeastern portion of Asia, space geodesy is the only technique that will provide quantitative constraints on both directions and rates of relative motions.

Some trench boundaries are conveniently characterized by islands on the subducting plate, at relatively short distance from the trench axis. These islands would make it relatively easy to establish and monitor fairly short baselines spanning the trench with which to determine the local convergence vector. This is unfortunately not always the case; without emerged land seaward of the trench at a reasonably short distance, we may have to rely on long baselines tying points far removed from the trench axis, and it becomes difficult to unravel the tradeoff that exists between apparent relative plate motion and plate deformation. In such instances, the emerging technology of precise sea-floor positioning provides an exciting alternative, particularly when even cm/yr observations are sufficient to test or even improve significantly our models.

3.1.3 Driving Mechanisms

Because the relative motions between plates constitute the known boundary conditions that any successful model of mantle circulation must satisfy, solutions to the kinematic problems described above will have a direct bearing on studies of the driving mechanism(s) of plate motion. Detailed discussion of plate driving mechanisms and mantle dynamics can be found in the contributions of other panels, notably the "*Earth Structure and Dynamics*" panel. The problem of mantle viscosity as constrained by rates of post-glacial rebound is discussed by the panel on "*Lithospheric Structure and Evolution*".

3.2. Regional and local deformation

Our understanding of the nature of and processes responsible for regional deformation varies greatly as a function of tectonic setting, age of deformation, seismic activity, surface exposure and physical accessibility. Our specific objectives for the next decade will thus vary greatly from one region to another, and must be individually tailored by a realistic assessment of existing knowledge of each individual area, physical accessibility, cost, and the needs of society.

3.2.1 Kinematics of deformation

Over the next decade, documentation of crustal kinematics and deformation must be the most basic goal of studies in regional and local deformation. Without kinematic data, informed development of theory describing crustal motion as the result of Earth processes and properties will not be possible. The time scales of interest in regional and local deformation span at least 13 orders of magnitude (see Figure 3) and include:

- Instantaneous motions, from seconds to hours
- Active motions of crustal fragments, averaged over years to tens of years
- Motions over recent earthquake cycles (10's to 1,000's of years)
- Holocene deformation
- Quaternary and older deformation in currently active systems

The length scales of interest span at least 9 orders of magnitude and include:

- Strain accumulation within crustal fragments (mm to cm)
- Displacement on and strain adjacent to individual fault (zones) (meters to 10's of km)
- Motions and internal deformation of coherent crustal fragments (10's to 100's of km)
- Net deformation across zones of plate boundary activity (100's to 1,000's of km)

Within a given tectonic system, motions and deformation occur over this entire spectrum and result in spatially and temporally complex patterns of superposed deformation. Of course deformation of the lithosphere involves not only horizontal and vertical motions at the Earth's surface and the development of surficial structures, but also affects the lower crust and the mantle. While subsurface deformation is generally not amenable to direct measurement, a large number of geological and geophysical data are sensitive to the way in which deformation is distributed with depth. In particular, gravity and topography data, which together are widely used to constrain the density structure of the Earth at depth, have proven a powerful tool for relating vertical and horizontal motions at the surface to subsurface deformation and to thermal and dynamic processes operating at depth.

An excellent example of the spatial complexity found in zones of plate boundary deformation occur within the Mediterranean region (Figure 4). At the largest scale this region comprises a zone of continental convergence and collision between the slowly moving European and African continents. At every smaller scale, tectonic systems within this broad region exhibit convergent, divergent and strike-slip motions in a large number of different directions. It is not uncommon for very different types of crustal motion and deformation to exist adjacent to one another, such as occurs in the Aegean-Hellenic subduction system in the Eastern Mediterranean where an area of active "back-arc" subsidence beneath the Aegean Sea exists adjacent to a zone of shortening and convergence along the Hellenic trench [eg. McKenzie, 1972, 1978a; Mercier, 1977]. At least enough is known about the kinematics of this system to relate subsidence of the Aegean sea floor to stretching and thinning of the underlying lithosphere, while subsidence of basins on the

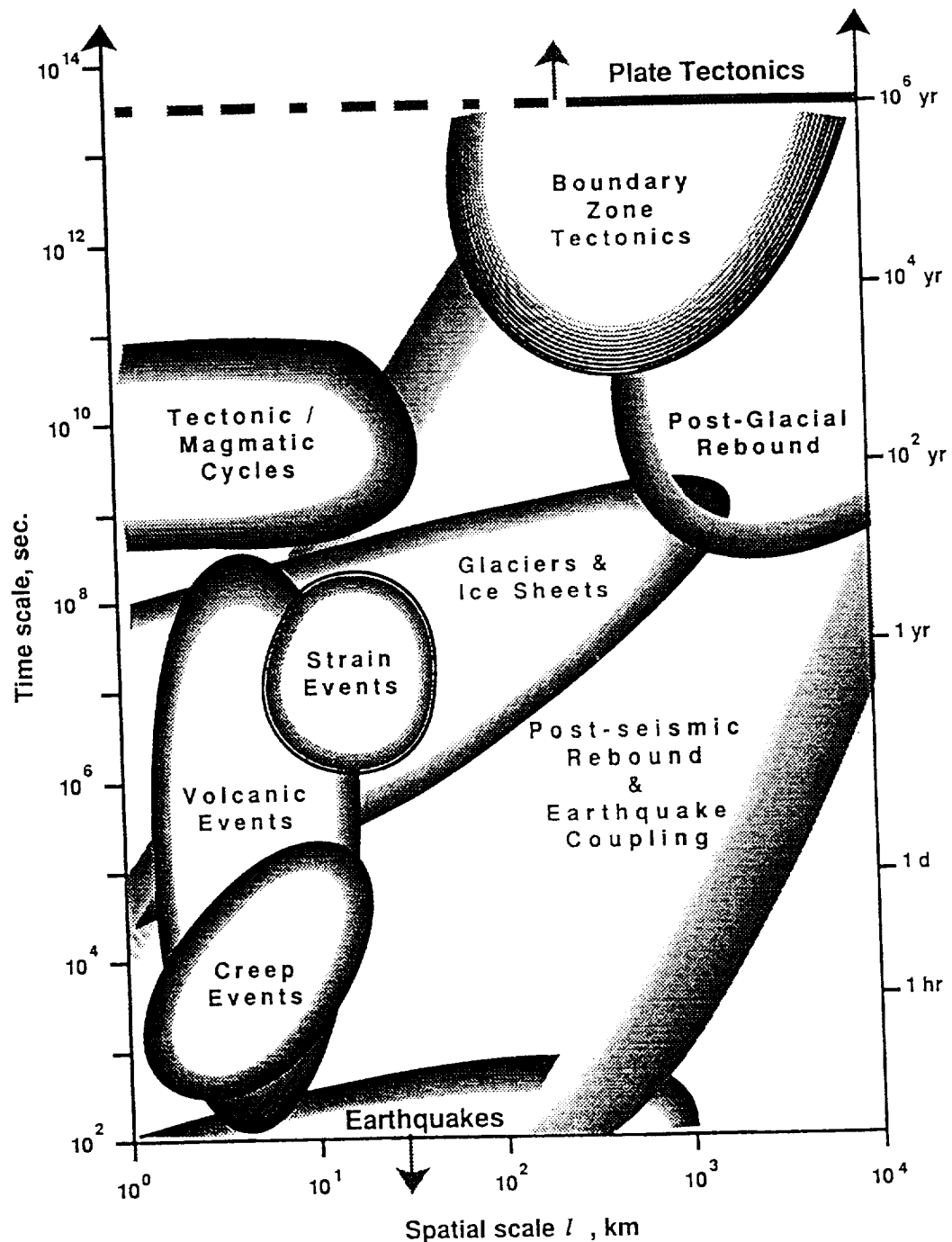


Figure 3. Spatial and temporal domains characteristic of various geological phenomena. The lower left portion of the diagram, at small spatial and temporal scales, is the domain of earthquake seismology, while the upper right is that of quaternary geology and plate tectonics. Most of the area covered represents the domains occupied by phenomena which must be studied through a combination of geodetic techniques, field geology, and tectonic interpretation. Except for the leftmost portion of the diagram, space geodesy is the only approach that yields the required quantitative measurements with sufficient spatial coverage and accuracy.

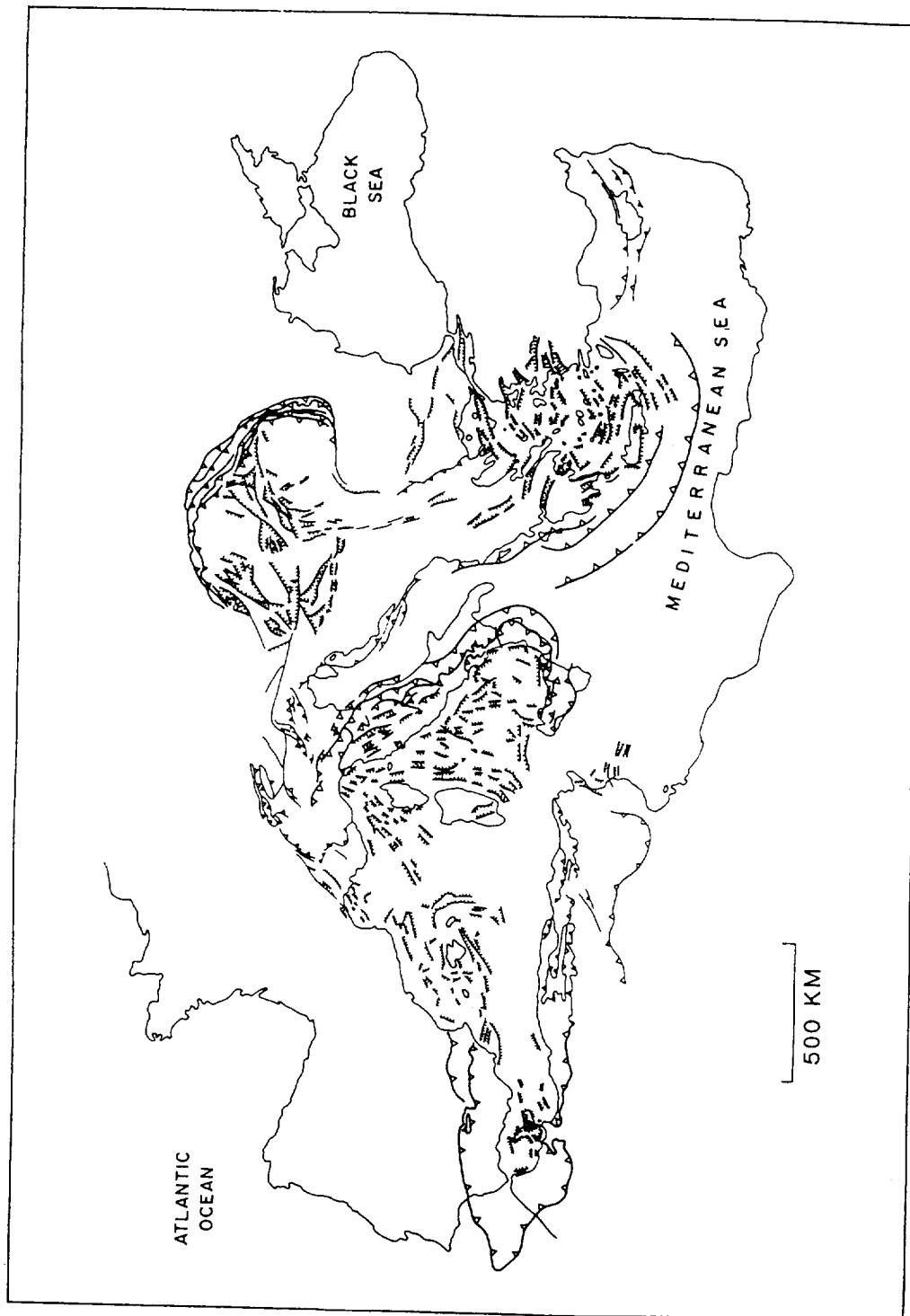


Figure 4. Late Cenozoic examples of thrust belts (with heavy barbed lines indicating thrust faults) associated with coeval back arc extensional systems (with heavy ticked lines indicating normal faults) in the Mediterranean region (from *Royden, 1988*). From east to west the thrust belt-basin pairs are (1) the Aegean-Hellenic system; (2) the Pannonian-Carpathian system; and (3) the Tyrrhenian-Apennine-Calabrian system.

opposite (foreland) side of the convergent zone is known to result from loading of flexurally strong foreland lithosphere by thrust sheets [McKenzie, 1978b; Moretti and Royden, 1988]. Careful constraints on the timing and magnitude of basin subsidence and thrusting show that there is a close connection between thrusting and extension in space and time, but the detailed kinematic and dynamic relationships between thrusting, extension and subduction remain poorly understood phenomena. It is only through documentation of the interaction between extension and convergence that the disparate types of deformation within this tectonic system can be understood as part of a single dynamic system that is related to flow within the upper mantle.

A substantial long term multi-national effort, the *Wegener-Medlas Project*, has been undertaken in 1984 to refine the kinematic picture of the Mediterranean region, and has begun to yield SLR data capable of placing useful constraints on the geological models (ie Wilson, 1987). The continuation of this project on a regional scale, and the densification of the network in critical areas (using, for example, GPS campaigns) will remain an important component of tectonic studies of the region in the coming years. These geodetic studies need to be augmented by careful geological observations and quantitative modelling of dynamic processes. In this area where overall kinematics and some processes are relatively well known, models of deformation and deformation processes will be much better constrained than in areas such as Tibet, and models developed to describe specific sets of observations are likely to prove fruitful.

Advancement of basic scientific knowledge requires study of a wide variety of processes in many different tectonic settings including detailed studies in areas where the over-all deformation history is known and reconnaissance studies in regions where the deformation history is poorly known. Specific objectives for the next decade will thus vary greatly from one region to another, but some of the universal issues that must be addressed through these studies can be illustrated through the following list of questions:

- How much of the overall strain is internal to crustal fragments, and how does it vary with distance from active faults?
- What are the short-term strains before and after major earthquakes and volcanic eruptions, and what are the controlling mechanisms?
- How do strain measurements from geodetic experiments compare to either seismic estimates or long-term geological estimates?
- How is displacement transferred from one set of faults to another, and what is the time scale for the reorganization of motions?
- What is the role of pre-existing structures within the crust for localizing deformation?

Some of these questions may be answered through analysis of geodetic data, but answers to most of them will rely on the combination of geodetic data with traditional geological field studies to examine the relationship between current and past deformation within a single tectonic or dynamic system. The combination of geodetic and traditional geologic data has the potential to provide insight into the nature of deformation that go far beyond those that can be provided from analysis of either type of data in isolation. We must begin now to establish basic constraints on active, historical and geological rates of fragment motions, including vertical and horizontal movement, and on the rates and style of regional deformation.

3.2.2 Dynamics of deformation

As we collect and refine our basic kinematic maps, we must continue to pose questions about the dynamic phenomena underlying the surface deformation. Over the entire spectrum of time scales for deformation, the relative roles of stress transmitted across the boundaries of crustal blocks and stress transmitted to the base of blocks by flow in the upper mantle remain major unanswered questions. Eventually we must address the

difficult questions pertaining to the dynamic mantle phenomena underlying the near-surface deformation in regions which are very active today. At present, techniques for measuring flow within the mantle on a regional scale are not yet available, but recent work that combines crustal kinematics, gravity data, velocity structure, and theoretical models for fluid convection show promise for the future [Hager and Clayton, 1989]. The implications for our understanding of mantle dynamics are enormous. This can be illustrated briefly by considering the deformation history of Tibet.

A number of studies suggest that deformation within Tibet involves movement of crustal fragments, with dimensions of tens to hundreds of kilometers, in directions oblique or even orthogonal to the overall direction of convergence between India and Asia (Figure 5) [Molnar and Tapponnier, 1975, 1978; Tapponnier *et al.*, 1982, 1986]. Preliminary data from northeastern Tibet show that, on a length scale of tens of kilometers, major deformation has switched from one system of faults to another and from one type of deformation to another over time intervals of less than a million years (Zhang, 1987). If mantle flow beneath Tibet can be linked spatially to the active movements of sizable crustal fragments, then the spatial variability of mantle flow must correspond to the motions of individual crustal fragments (which can be measured using space-positioning techniques), while the temporal variability of mantle flow must occur over the same time scale as changes in the direction and rate of movements within the crust (which can be dated using traditional geological techniques and remote sensing data). Alternatively, if mantle flow can be shown to be related to crustal motion only at the scale of the entire plate boundary, then one might suspect that the temporal variability of flow in the mantle corresponds to that of the entire plate boundary zone (10^7 - 10^8 yr, e.g. England *et al.*, 1985).

The processes that control earthquake and volcanic cycles also require considerable attention and comparisons between crustal kinematics, seismicity and other geophysical data are crucial to achieving a quantitative understanding of these phenomena. Crustal deformation patterns associated with the earthquake cycle, particularly surface displacement, displacement rates, strain, and strain rates, depend strongly on the rheological properties of crustal and subcrustal material near the seismogenic zone [Cohen and Kramer, 1984]. Over the past 15 years a number of viscoelastic models of deformation near major strike-slip faults have been proposed; these models differ in their predictions concerning the temporal and spatial patterns of crustal deformation throughout the seismic cycle [Nur and Makvo, 1974; Turcotte and Spence, 1974; Rundle, 1978; Prescott and Nur, 1981; Yang and Toksöz, 1981; Thatcher, 1983; Cohen and Kramer, 1984; Thatcher and Rundle, 1984; Li and Rice, 1987].

Ideally, we would like to be able to combine large scale geodetic or geologic information about relative plate motion, rheologic properties of the crust and upper mantle near the boundary, and the geometry of the plate boundary to understand how deformation is distributed through time, where faults develop, what their slip rates are, and how fault patterns evolve with time. Of particular note is the need to establish permanent networks of geodetic instruments in areas of frequent volcanic or seismic activity, so as to maintain a continuous record of short-term ground motions immediately before and after major eruptions and earthquakes and to aid in their prediction. Several regions where large earthquakes or volcanoes are predicted to occur in the 'near' future should be selected and measurements begun, so that we can will begin to accumulate complete sets of observations spanning all parts of the seismic cycle, in a variety of tectonic environments. Such studies will require densely monumented geodetic networks and a rich environment of supplementary studies, including geologic and seismologic investigations. For example in California, the large number of densely spaced seismic stations, extensive geologic mapping of quaternary and holocene structures and detailed maps of gravity and heat flow, in combination with horizontal and vertical geodetic observations on scales from a few meters (creepmeters and strainmeters) to hundreds of kilometers has resulted in one of the best understood plate boundaries in the world. Yet even with the rich panoply of

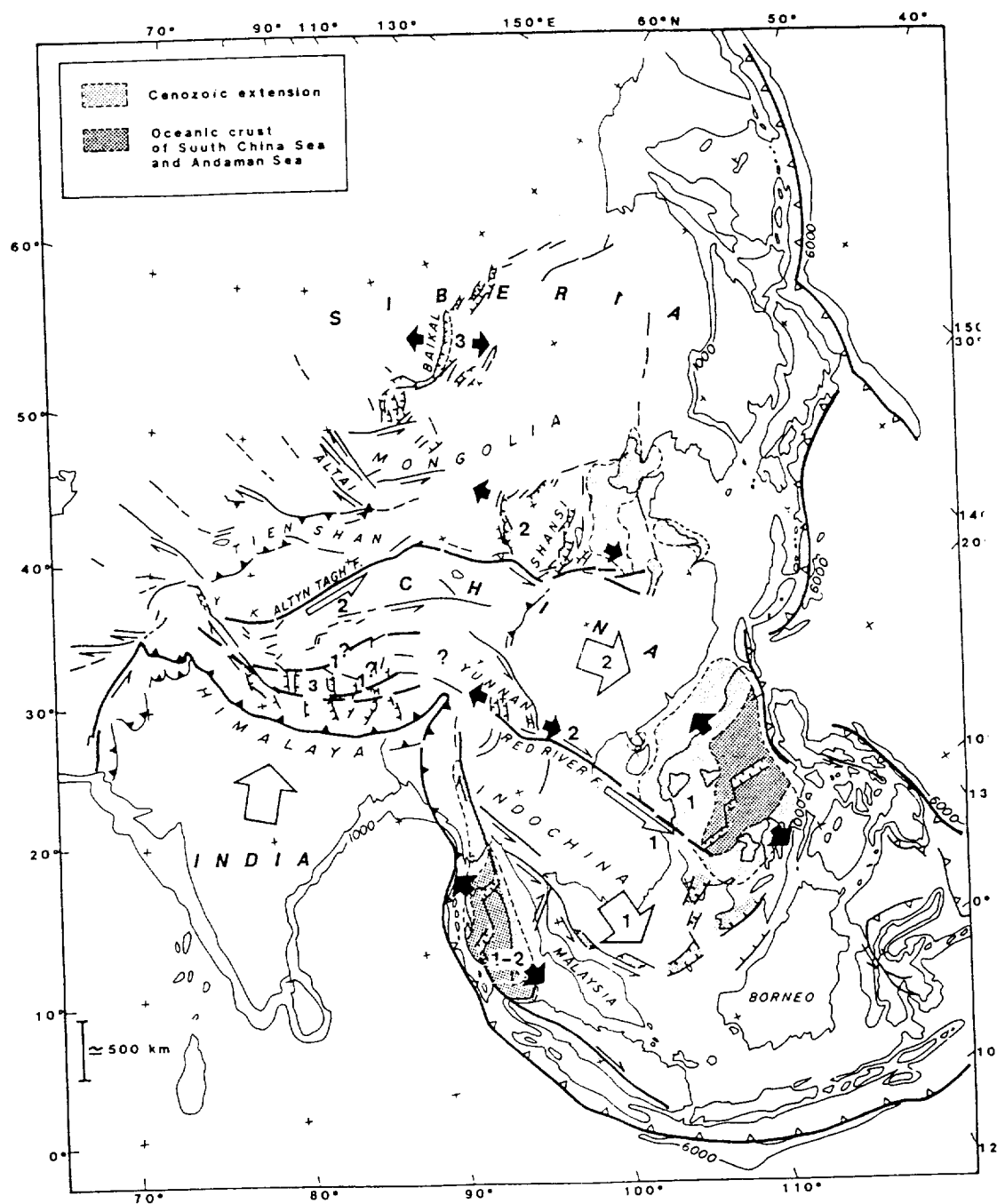


Figure 5. Schematic map of Cenozoic tectonics and large faults in eastern Asia (from *Tapponnier et al.*, 1982). Heavy lines are major faults of fault boundaries, thin lines are less important faults. Open barbs indicate subduction, solid barbs indicate intra-continental thrust faults.

observations available in California we are far from a comprehensive understanding of how deformation occurs during earthquakes and over the earthquake cycle.

3.2.3 Internal deformation of large plates

There is convincing geological evidence that some plates are deforming on million year time scales and suggestive evidence that deformation of oceanic plates may be occurring on even the short time scales spanned by space-geodetic techniques. Questions that can be effectively addressed by space geodesy include:

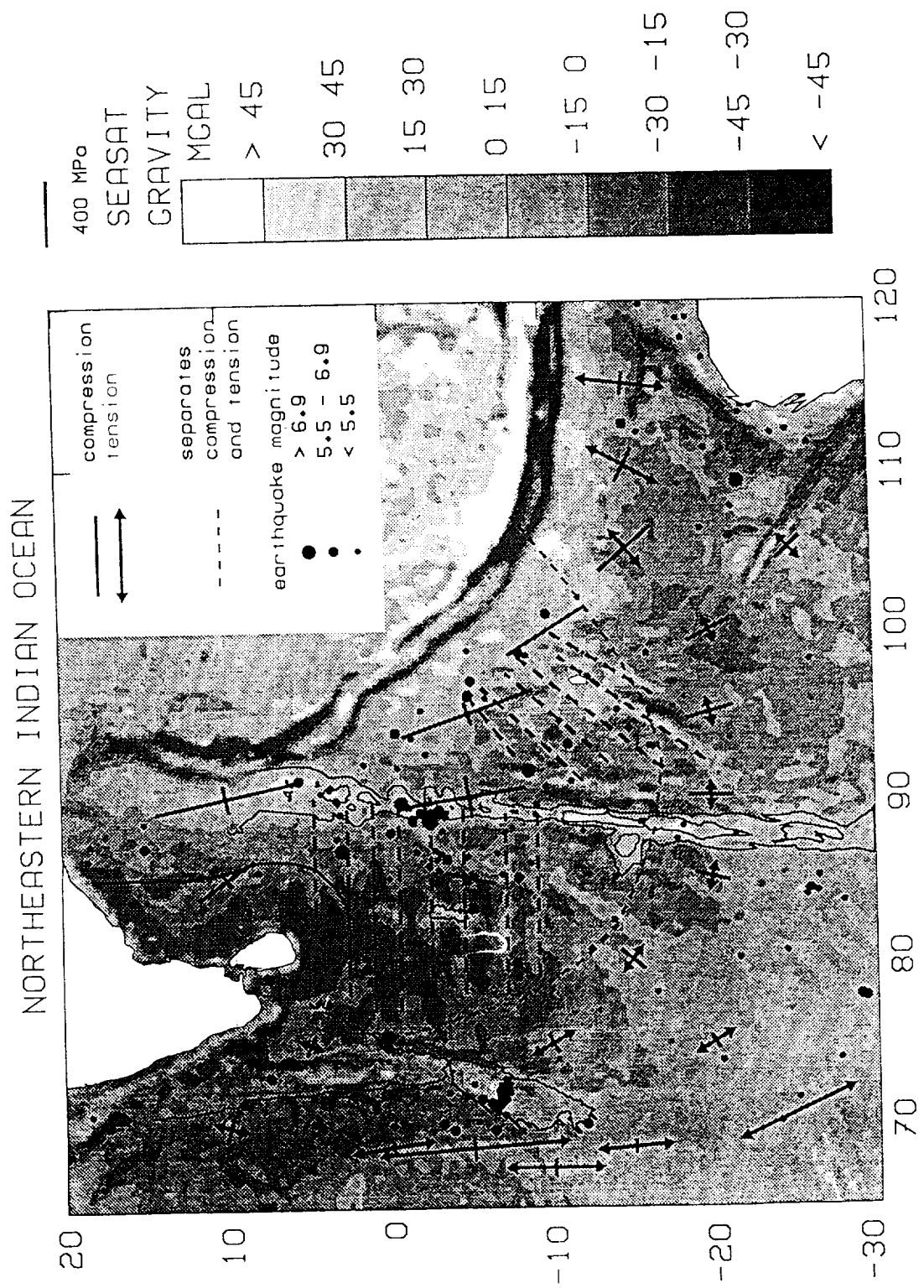
- Does diffuse deformation occur in zones much smaller than typical plate dimensions or over the plate as a whole?
- Do diffuse deformation zones tend to evolve into simpler, narrower boundaries?
- Even though most plates may behave rigidly to a good approximation over 10^6 year time scales, what happens over short and intermediate time scales?
- Can we detect, by space-geodetic techniques, differences between the behavior of continental and oceanic areas?

For regions that are largely inaccessible to direct geologic mapping due to water (Pacific plate) or ice (Antarctic plate), space geodesy appears to be the only means of resolving internal deformation of these plates. For example, within the Indian plate deformation of sedimentary cover into east-west-trending ridges south of the Bay of Bengal and associated gravity anomalies and intraplate earthquakes suggest that the Indian plate is buckling in response to the collision with Asia (Figure 6). This interpretation is supported by observations of the relative motions of plates adjacent to the Indo-Australian plate, which have motions inconsistent with a completely rigid Indian/Australian plate [e.g., *Gordon et al.*, 1988]. Baseline geodetic measurements from India to Australia will provide a powerful and definitive test of this hypothesis.

Another example of possible nonrigid plate behavior is suggested by very preliminary TLRS results collected over the past 6 years: Huahini, an atoll near Tahiti, is moving away from Hawaii at the rate of 6 ± 5 mm/yr [*Smith et al.*, 1989b]. In the absence of a sufficiently dense geodetic network linking Huahini to neighboring islands, the areal extent and meaning of this deformation are unknown, but if confirmed, it might be linked to the origin of large scale depth, geoid, and seismic velocity anomalies in French Polynesia [*McNutt and Fischer*, 1987]. However, we must examine carefully possible tradeoffs between apparent horizontal and vertical motions.

There is a need to relate the geodetic observations to the geology if we are to draw geologically valid inferences from any evidence of deformation. Since regional geological history may be difficult to establish directly in some cases, present-day rates derived from space geodesy must then be compared to other geophysical observations such as intraplate seismicity, volcanism, seismic velocity anomalies, small-scale gravity features, etc., to investigate the causes and consequences of intraplate deformation.

Figure 6. "Intraplate" earthquakes, gravity anomalies [*Haxby*, 1987], and predicted stresses from the model of *Cloetingh and Wortel* [1985] in the northeast Indian Ocean. Note that the orientation of the gravity highs corresponding to the buckled oceanic lithosphere agrees with the orientation predicted by the compressional stress field. The undulations are not observed far south of the predicted transition from compressional to tensional stresses. The undulation patterns at 3°S , 83°E are distorted by the Afanasy Nitikin seamounts. The Chagos-Laccadive Ridge is outlined by its 3.5-km contour. The seamounts and Ninetyeast Ridge are shown by 2.5-km and 4.0-km contours. From *Stein, Cloetingh, and Wortel* [1989].



3.3 Societal impact

Study of plate motions and deformation is not motivated solely by a quest for knowledge but also as a means to achieve a reduction in natural hazards, particularly in the prediction of earthquakes and volcanic eruptions, and in the assessment of global warming and climate change. Comparisons between crustal kinematics, seismicity and other geophysical data are crucial to achieve a quantitative understanding of seismic and volcanic phenomena. Several historical examples serve to illustrate the incredible damage and loss of life that may accompany seismic and volcanic disasters. In 1556 AD an earthquake occurred in a tectonically active region near Shensi, China with a probable magnitude greater than eight. It killed more than 800,000 people. This is the largest loss of life recorded from any one earthquake, but is not unique in China's history. More recently the Haiyuan earthquake in 1920 and the Tangshan earthquake in 1976 each killed more than 200,000 people. In approximately 1200 BC an explosive volcanic eruption roughly 15 times larger than that of Krakatoa occurred on the island of Santorini in the Aegean Sea. This eruption is thought to have been responsible for the destruction of the Minoan civilization. The potential for a similar eruptions in the western US underlines the need to understand and eventually predict these natural phenomena.

A comprehensive discussion of applications to the mitigation of volcanic hazards is given in the report by the panel on volcanic problems. Similarly, continued national and international effort toward a better assessment and understanding of seismic hazards will benefit directly from the investigations mentioned in the preceeding sections, and from improved geodetic measurement techniques. In this sense, the study of plate motion and deformation can make a significant contribution to multi-agency, multi-national and multi-disciplinary programs aimed at making progress in this area.

Perhaps even more important is the need to monitor global warming by measuring sea-level rise to evaluate the rate of melting of the polar ice-caps. This will require significant improvement in plate deformation measurements, including determination of reliable measurements of surface vertical movements on regional and global scales. More substantial discussions can be found in companion reports, such as those prepared by the "*Earth Structure and Dynamics*" and "*Lithospheric Structure and Evolution*" panels.

4. REQUIREMENTS

The next frontier in global plate kinematics and dynamics clearly lies in resolving small, departures from the standard models. In this section, we shall summarize the precision requirements needed not merely to detect plate motion and deformation, but also to test and refine existing models. In addition to the measurement accuracies needed from space technology, general requirements of any program to model plate motion and plate deformation in the 1990's will include ongoing efforts to develop new models, compare instantaneous rates with geologically-inferred ones, and interpret motions within the geodynamic context through integration with other geophysical data.

4.1 Horizontal Motions

4.1.1 Plate Motions

It is difficult to estimate the measurement accuracy required to resolve time-dependence in plate motions. We have no firm basis for predicting the amplitude or the characteristic time scale of such motions on a plate-wide basis. A few plate thicknesses away from plate boundaries, we can expect transients following large earthquakes, but these will not propagate with large amplitude into the plate interiors if current rheological models are correct. Nevertheless, it is not unreasonable, as an initial hypothesis, to suppose that

accelerations in plate motion would be either caused by, or the cause of, time-dependent behavior along plate boundaries, such as earthquakes, creep events, rapid pre- or post-seismic motions, etc. Therefore, any program to measure variability in plate motions should be coordinated with deformation measurements on the corresponding plate boundaries.

The most important measurement requirement when trying to detect and document time dependent motions is that we avoid temporal aliasing by frequent surveys. The finite nature of resources then demand that this kind of monitoring be restricted to a rather coarse network until such time as an "interesting signal" is detected. Of course, if such a signal is indeed detected, we will have to respond with a coordinated investigation involving densification of the network around the sites of interest. Another important consideration is that we must consider this type of monitoring to be a long-term endeavor. Thus, detecting variations in plate speeds over decadal time scales cannot be achieved without a long term commitment to the acquisition of long time series of high-quality data. Even with the present technology we should be able to detect time-dependent plate motions at the sub-millimeter level provided we patiently accumulate continuous time series over several decades.

To refine significantly models of plate motions in regions where they are most uncertain (i.e. have an reliability on the order of 10 mm/yr), would require monitoring a number of well-selected baselines with an accuracy of 1-4 mm/yr (although even 10 mm/yr can be of great value in certain areas such as Southeast Asia). The requirements in terms of accuracy are similar, 1-5 mm/yr, for the problem of determining plate geometry in regions where the location and nature of plate boundaries is uncertain. A fiducial network will not have the dense coverage necessary to locate plate boundaries and determine the rate of relative motion across them. Repeated surveys at 10^2 to 10^3 km spacing using techniques such as GPS, GLRS, or mobile VLBI and SLR, should meet the accuracy and resolution requirements, provided the regional survey is tied to a high-quality fiducial net.

4.1.2 Regional and local deformation

Application of space geodesy to regional deformation will require a precision in horizontal positioning considerably greater than that needed to merely detect the movements of large plates on a global scale. Ideally, one would like to resolve horizontal motions within zones of plate boundary activity to better than 5 to 10% of the rates of motion between the adjacent plates. Rates of relative motion between the large plates fall into the general range of about 10 to 100 mm/yr, so that resolution of motions at rates of 0.5 to 5 mm/yr are needed to document the partitioning of strain within plate boundary zones. If significant results are to be obtained within a reasonable period of time - perhaps five years - measurement accuracy of about 1 mm in horizontal positioning will be needed. There will be a large payoff in the improvement of horizontal positioning techniques in the range between 1 and 10 mm. With a horizontal resolution of 10 mm, even rudimentary partitioning of strain can be obtained only within the more rapidly deforming regions, while partitioning of strain within more slowly deforming areas will be difficult to obtain without experiments that run for many decades. Improvement in accuracy to a few mm/yr will be sufficient to resolve the partitioning of active deformation in the more rapidly deforming regions on a relatively fine scale, as well as the basic features of strain fields in more slowly deforming regions.

Logistical considerations will be crucial in determining the practicality of applying space positioning techniques to problems in regional deformation, particularly in remote areas. Except in the most densely populated regions, geodetic surveys will depend upon the repeated occupation of geodetic sites using portable instruments rather than on the maintenance of permanent facilities. Instruments need to be sufficiently lightweight to be carried on foot for short distances (1 km or so), and yet sturdy enough to stand up to transportation by air and by truck over bad roads. The need to carry out geodetic surveys

in a reasonable time period requires that the instruments must be capable of obtaining the desired level of accuracy in a time period of no more than about two days, preferably less. For example, a typical network might consist of 10 to 15 sites. If two instruments are moved continuously while one or two other instruments remain fixed, a complete survey of the network may be completed in roughly four to six weeks, assuming 2 days for measurement at each station and 2-3 days for transport between stations.

Different logistical problems exist in densely populated areas where frequent or intense seismic or volcanic activity poses a hazard to large numbers of people. In such regions it will be necessary to maintain a dense network of continuously monitoring geodetic facilities, so as to maintain a record of pre- and post-seismic deformation. It may make sense to deploy seismic and geodetic instruments together as part of a single network. The cost per instrument and the man power required to maintain the instruments will become crucial if a large number of stations are to be established, with inter-site spacing from perhaps 3 to 30 km. If pre- and post-seismic deformation are to be measured, then it will be necessary to obtain the desired levels of accuracy in the shortest time possible - roughly hours to days. The large spatial density and high rate of sampling in these networks will make it possible to treat crustal deformation in the same way as digital seismic network data, using standard techniques of digital data processing to eliminate spatial and temporal aliasing effect, to stack the data in various ways in order to bring out particular strain patterns, etc. This has generally not been possible with crustal deformation data before.

A global network of fiducial stations will be needed for all regional and local surveys, to tie local and regional deformation patterns to global motions of the major plates, and to separate local effects from large-scale plate deformation. Our requirement for global coverage with a sufficiently dense, high precision fiducial network is the basis for our main recommendation for the next decade.

4.1.3 Non-rigid plate behavior

The overall success of the rigid-plate motion models indicates that non-rigid behavior of plates is limited to rates of less than a few mm/yr over million-year time spans. Over shorter time intervals, lack of data prevents us from making trustworthy predictions. We have an overriding requirement, namely that it will be critical to distinguish between broadly distributed non-rigid plate behavior and localized tectonic deformation. Any signal suspected to be caused by the breakdown of the rigid plate assumption detected with the fiducial network must be followed up with densification campaigns 1) to ascertain whether the signal is indeed due to a regional effect instead of to the motion of a single site, and 2) to measure the area over which the effect is detectable because data interpretation will depend critically on the spatial scales encountered.

4.2 Vertical Motions

Except for vertical motions induced by post-glacial rebound —typically 10 mm/yr— most vertical motions are at least an order of magnitude slower than horizontal motions. Only in tectonically active areas with very rapid erosion or tectonic denudation (and in areas subject to post-glacial rebound) do rates of vertical motion reach as much as 1 mm/yr. Because vertical motion is dominated by post-glacial rebound at large spatial scales (Figure 7), we must document and understand post-glacial rebound before other contributions to the vertical signal can be isolated. These requirements are described by the panel on "*Lithospheric Structure and Evolution*".

Uplift rates related to dynamic stresses or heating and cooling of the lithosphere are typically a few tenths of a mm or less. For example, geobarometry on metamorphic rocks from central Nepal indicate that 20 km of uplift and erosion has occurred in the last 20 Ma, giving an average uplift rate of 1 mm/yr. While it is not known how uplift has been partitioned through time, although it is generally thought that uplift rates in mountain belts

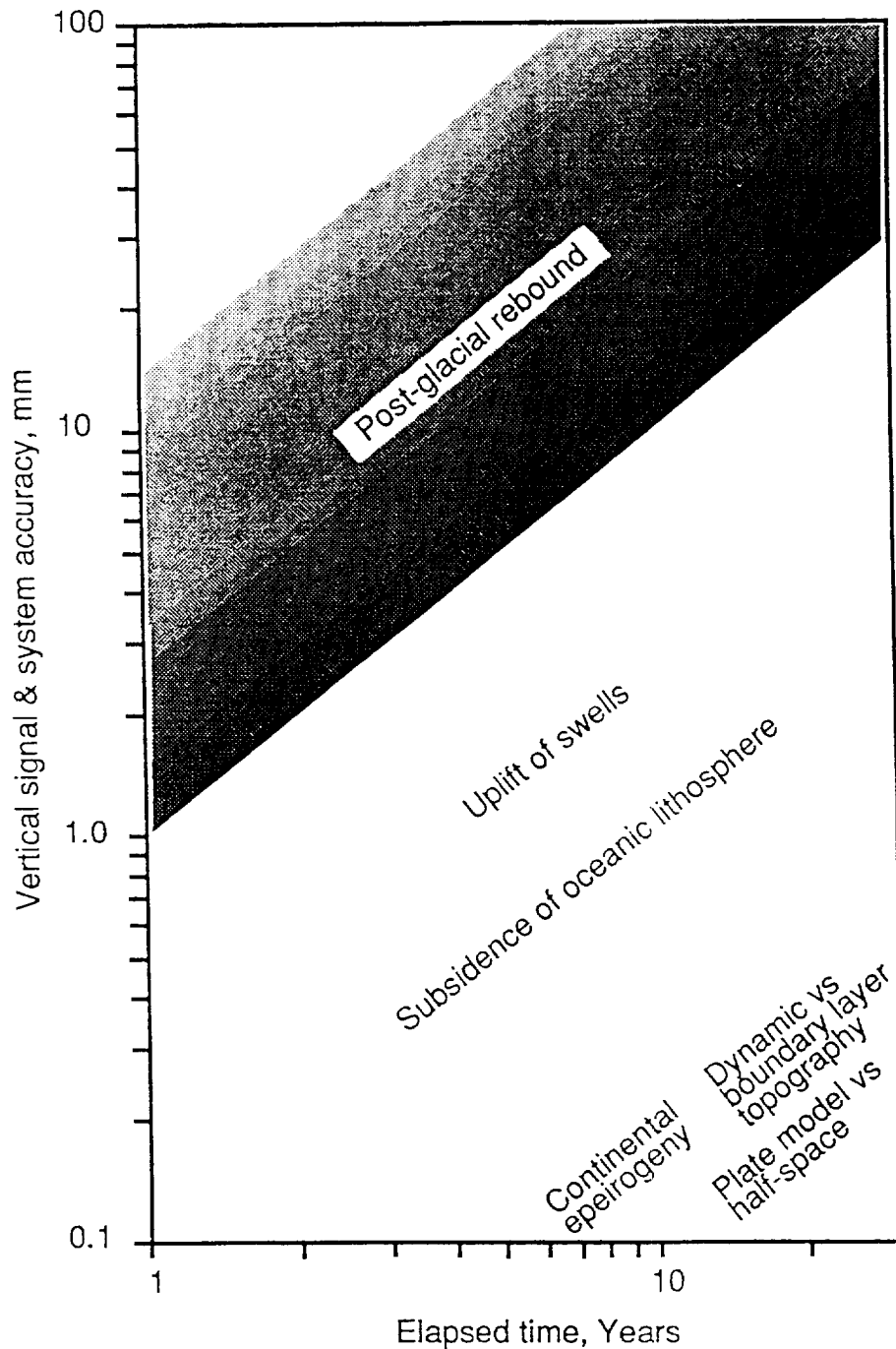


Figure 7. Vertical geodetic signals which can be treated as steady-state over decadal time spans are characterized by much slower rates than horizontal signals, except for post-glacial rebound. Even if a very long term program is initiated to measure directly these signals, the interpretation of the data will require first that the post-glacial rebound contribution be thoroughly understood and modeled before other, much smaller contributions can be interpreted reliably.

seldom exceed a couple of mm/yr. In regions of extensional tectonics, such as in the Basin and Range Province, uplift of footwall rocks beneath low angle detachment faults by about 15 to 20 km is thought to occur over a time period of a few million years, yielding an average uplift rate of a few mm/yr and comparable to uplift rates inferred for rapidly eroding mountain belts. Because these are the maximum rates of long-term uplift or subsidence that are likely to be observed, vertical positioning with accuracies of one or two mm are critical. Higher rates of vertical movement may occur as short-term phenomenon near active faults and volcanoes (some numbers), so that monitoring of vertical movements in these regions at the cm level of accuracy may be rewarding. Except as regards study of short-term, local deformation near active faults and volcanoes, and study of post-glacial rebound, vertical positioning with accuracies poorer than one or two mm will be useless.

Rates of subsidence from cooling of the lithosphere are about an order of magnitude less than those resulting from active deformation. For example, in sedimentary basins that form by extension, basement subsidence of 5 km in a couple of million years is not uncommon, yielding subsidence rates of perhaps 2 mm/yr. In contrast, during the thermal cooling portion of the basin subsidence, rates of about 1 km in 10 my are the largest observed, or 0.1 mm/yr. Rates of uplift or subsidence from dynamic processes are likely to be similar or larger by a factor of two to three. For example, the Hawaiian island chain has been uplifted by roughly 2.5 km in 8 my, yielding rates of roughly 0.3 mm/yr. Thus geodetic measurement of vertical motions resulting from dynamic and thermal effects in the Earth's interior require the resolution of motions of 0.1 to 0.3 mm/yr. Clearly this level of accuracy is beyond our reach within the next decade. With precision of about 1 mm/yr, it may be possible to resolve these rates with experiments that last several decades, but it is futile to begin such studies until we have the capability of vertical positioning to at least 1 mm.

The logistical requirements for vertical positioning are rather different from those required for horizontal positioning. Accuracy is much more important than speed in obtaining measurements, and the feasibility of continuous monitoring should be considered for carefully selected sites in which rates of uplift or subsidence are key in constraining the nature of thermally, dynamically or tectonically driven processes in the Earth's interior.

4.3 Satellite Images

Satellite images have revolutionized our ability to map neotectonic structures on a regional scale and have proven to be an indispensable tool for geological mapping. Landsat 4 and 5, carrying Thematic Mapper (TM) with 7 spectral bands and a higher spectral resolution than the older Landsats, provides excellent data at 30 m resolution. While the current resolution of these images is sufficient for many purposes, improvement beyond the 10-30 m range will enable geologists to map structures and neotectonic features at a level of detail not now possible. For study of landforms resulting from local deformation and faulting, an improvement to 1 m resolution, even at a single spectral band, will allow geologists to map fault offsets resulting from even a single earthquake. A more general discussion is given by the panel on "*Landforms and Paleoclimate*".

A significant impediment to using current high resolution satellite data for regional studies is the high cost of the data (\$3,000 to \$4,000 per 180 km square for TM and about four times more for SPOT). This is unfortunate because large remote regions, requiring numerous scenes for adequate coverage, are precisely the areas where this data is most sorely needed. Therefore, a high priority for satellite imagery in the next decade should be to provide systems whereby data comparable to Landsat 4 and 5 for all continental regions, and higher resolution images for selected areas, are readily available at moderate cost. Emphasis should also be placed on developing a system that can distinguish between various lithologies on the ground, thus improving the ability to extend local field mapping studies to more regional scale using satellite images. For these reasons, we anticipate that a

number of facility instruments planned for the Eos mission (e.g. MODIS, HIRIS), together with the associated data information system (EosDIS) will have a very favorable impact on our understanding of regional deformation and related geological phenomena.

4.4 Topography

A global, coherent data set with moderately high accuracy (10 m vertical and 1 km horizontal) is needed to support interpretation of satellite-derived gravitational and magnetic data acquired over continental areas. The target sensitivity of the next generation gravitational satellite will be on the order of 2.5 mgal surface gravity at 100 km horizontal resolution. At these wavelengths, an error in topography of 1 m will cause an equivalent error in the gravity anomaly measured by the satellite (at 160 km orbit) of about 0.1 mgal. Thus a maximum of 10 m uncertainty in the height measurement will ensure that topographic variance is not a limiting noise source for gravity measurements. The requirements for interpretation of magnetic data are less stringent.

Identification of structural features as a clue to neotectonic activity clearly requires very fine resolution of topography, perhaps 1 m vertical and 10 m horizontal would be ideal for most purposes (equivalent to about 1:50,000 topographic sheets). This higher resolution topographic data set need only be acquired once for most problems in regional and local deformation. What is needed is a moderately high resolution data set (10 m vertical and 1 km horizontal) for all continental areas, with higher resolution data in selected areas - particularly those tectonically active areas with rugged topographic relief. For studies of dynamic morphology, the evolution of topography as a function of time becomes paramount, so repeated precise topographic surveys will be needed. An extended discussion of these issues is provided by the panel on *"Landforms and Paleoclimate"*.

4.5 Gravity

The Earth's gravity field, together with its topography, is a direct reflection of subsurface processes that produce horizontal and vertical motions at the Earth's surface and within its interior. As discussed by the panel on *"Lithospheric Structure and Evolution"*, gravity data are crucial in assessing the strength of the lithosphere in a variety of tectonic settings and the spatial and genetic relationships between applied loads and vertical deflection at the Earth's surface. Gravity data will also be critical in determining the role of mantle flow beneath actively deforming regions, because convective patterns within the mantle, whether driven by thermal or compositional buoyancy, produce dynamically maintained topography at the Earth's surface, at the core-mantle boundary, and at other internal density interfaces. Because zones of regional deformation at the surface of the Earth consist of interactions along crustal fragment boundaries typically a few tens to a few hundreds of km in width, most applications of gravity data to problems in regional deformation require accuracy of 1 to 2 mgals at a spatial resolution of 20 to 200 km. Since the lower limit on spatial resolution for satellite gravity data is roughly 50 km, some problems in regional deformation and dynamics cannot be addressed directly through satellite gravity data and must rely on airborne and surface measurements. However, collection of such observations over much of the Earth's land surface is an onerous task, and satellite gravity data is at present the only available source of adequate gravity coverage in many regions, and will remain so for some time to come.

For many problems in regional deformation and dynamics, a 100 km spatial resolution seems to mark a critical divide: at better resolutions a wide range of important problems can be addressed, including many aspects of the thermal structure of the continental lithosphere and driving forces for continental tectonics. At poorer spatial resolution, few problems in regional deformation can be constrained by gravity data. Therefore development of the capability for obtaining satellite gravity data accurate to 1-2 mgal or better at 50-100 km spatial resolution during the next decade must be a high priority.

4.6 Magnetism

Oceanic and continental swells that are suspected to be thermal in origin, such as beneath Bermuda, Hawaii and East Africa, are typically 500 to 1500 km in diameter. If magnetic data are to be used to infer the thermal structure beneath these regions, a desirable spatial resolution for magnetic data would be perhaps 100 kilometers. Similar spatial resolutions would be required for the Tibetan plateau and many sedimentary basins. An accuracy of a few nT should suffice for reconnaissance work. However, at the present time, little research has been conducted on the use of magnetic signatures in regional deformation problems. This may well change in the next 10 years as we obtain better maps of the crustal field. An accuracy of 1 nT with a horizontal resolution of 100 km is a suitable goal for global coverage, although local resolutions of 1 km or better will be needed to evaluate the existence and usefulness of signatures associated with local deformation. As in the case of gravity, these requirements call for a combination of satellite, aircraft, and ground observations.

4.7 Modeling and Data Synthesis

A reasonable understanding of regional deformation cannot be developed using only one type of observation. The need to consider a phenomenon from several observational aspects is an integral part of the scientific method - without it we cannot hope to obtain the insights we seek. Emphasis must be placed on the thoughtful integration of geodetic, topographic, gravity and magnetic data, and space images, with one another and with ground-based geophysical and geologic observations. For example, geodesy may ultimately provide detailed velocity maps for much of the Earth's surface - without doubt a significant achievement in its own right. Yet even at a high level of detail, regional strain nets can at best resolve present day rates of motion between various parts of a broad plate boundary. In isolation, regional strain nets cannot provide answers to fundamental questions about how strain is accommodated, in what ways and how quickly the spatial distribution of long-term deformation may change with time in a geologic system, and how mechanical and dynamical connections unify disparate types of deformation into a single coherent tectonic picture. Only by combining geodetic information with geological and geophysical data and with theoretical geodynamic models can we hope to understand fully the motions at the Earth's surface and to relate them to processes within its interior.

Similarly, without the use of geologic field data, geodetic and geophysical techniques provide only a snapshot of the present state of complex regional dynamic systems. Because regional deformation and the motions of lithospheric and crustal fragments must be understood in light of time dependent flow within the mantle, crustal dynamics will ultimately depend on geologic field data to establish temporal constraints on crustal motions and on mantle flow beneath active plate boundary regions. In order to progress in our understanding of the physics of crust-mantle interaction and mantle flow, we must turn to a joint interpretation of geodetic observations, geophysical data, and geologic reconstructions of crustal motions.

Acquisition of data to constrain regional deformation must proceed hand in hand with the development of theoretical models that link surface deformation and motions to flow in the Earth's interior and to the thermal and mechanical structure of the lithosphere. Ultimately, we must develop models that provide a genetic link between different types of phenomena, and that can be tested through analysis of existing data or of data to be collected during future operations. Theoretical models are essential to any well-founded program of observations, in that they can help to direct future acquisition of data towards areas that will most efficiently test the dynamic framework within which we view Earth processes. Conversely, these models must be continuously reviewed and modified to incorporate new data and concepts. In this way both theory and observations play important and complementary roles in the formulation and testing of geological hypotheses.

4.8 Summary of Requirements

Table 1 summarizes the requirements discussed above. It must be borne in mind that these requirements are those placed by scientific problems related to plate motion and deformation, and are therefore not necessarily adequate to address other geophysical and geological problems discussed by other panels. Of these requirements, those listed for vertical motions are clearly the most demanding ones; except for the measurement of vertical motions due to post-glacial rebound, they are by and large inaccessible to current technology. Consequently, the focus of our efforts to measure vertical motions should remain on issues related to post-glacial rebound for the moment, for this term will mask the other signals, until such time as the technology improves significantly.

Finally, it must be noted that even more stringent requirements of horizontal resolution of field and topographic data may exist locally, but not globally. This means that special attention needs to be paid to the merging of space-geodetic data sets with the results of ground or air-borne techniques in these areas.

Table 1. Measurement requirements

Measurements	Precision required	Spatial scale/resolution
<i>Horizontal motions</i> Variability of plate motion Vector motion between plates Nonrigid plate behavior Regional and local deformation Post-seismic deformation	1-10 mm/yr 1-10 mm/yr 1 mm/yr 1 mm/yr 10-100 mm over hours	10^4 km $10^2 - 10^3$ km 10^3 km $10^1 - 10^2$ km $10^0 - 10^2$ km
<i>Vertical motions</i> Post-glacial rebound Active vertical tectonics Thermal & dynamical processes Continental epeirogeny Post-seismic deformation	1 - 4 mm/yr 0.1 - 1 mm/yr 0.01 - 0.1 mm/yr 0.03 mm/yr 10-100 mm over hours	$10^3 - 10^4$ km $10^1 - 10^3$ km $10^2 - 10^3$ km 10^3 km $10^0 - 10^2$ km
<i>Satellite images</i> Regional studies Local and neotectonic studies	10 - 30 m multispectral 1 m single band	$10^2 - 10^3$ km $10^0 - 10^2$ km
<i>Topography & altimetry</i> Global continental topography Global oceanic bathymetry Local topography	10 m vertical 10 m vertical 1 m vertical	1 km 20 km 10 - 100 m
<i>Gravity</i> Regional tectonic studies Local tectonic studies Post-glacial rebound	1 - 2 mgal 0.1 - 1 mgal 1 μ gal	50 - 100 km 10 km 1000 km
<i>Magnetics</i> Global crustal anomalies Local anomalies	1 nT 1 nT	100 km 1 km

5. RECOMMENDATIONS

5.1 Basic Recommendations

Our panel has four specific recommendations:

[1] In order to study plate motion we need a global distribution of geodetic stations that measure relative positions to 1 cm over one day and to 1 mm over three months. In order to monitor regional and local deformation we need a terrestrial reference frame. Both of these objectives can be accomplished with a global distribution of space-geodetic observatories.

This can be best accomplished by:

- deploying a world-wide network of dedicated, continuously monitoring GPS stations with 1000 km spacing and measuring relative positions to 1 cm over one day and to 1 mm over three months. Approximately 150 stations will be required on the continents with another 50 stations located on islands, for a total of about 200 stations;
- deploying a full constellation of GPS satellites to support this network.
- continuing a world-wide network of approximately 12 VLBI/SLR sites with at least one on each major plate and several distributed around the Pacific Ocean. These sites must maintain relative positions to 1 cm over one day and to 1 mm over three months to determine Earth orientation and GPS fiducial coordinates;
- co-locating GPS receivers at other existing VLBI/SLR stations and ceasing to occupy these stations as soon as it can be done without loss in precision and without offsets in the data series.
- continuing a network of SLR stations with positions relative to the Earth's center-of-mass determined with sufficient accuracy to provide adequate orbits for the GPS satellites. At such time as GPS (or some other system) demonstrates a capability of meeting center-of-mass requirements at the same level these SLR sites will no longer be required for this purpose;

[2] In order to monitor deformation in tectonically active areas where deformation is concentrated, we need a finer spacing of geodetic sites. We recommend the initiation of a vigorous long-term program of monitoring regionally dense networks deployed across tectonically active regions, to measure and analyze motion and deformation over a broad range of spatial and temporal scales.

- Some obvious scientific problems include: the kinematics of major plate convergence systems; the distribution and rate of post-glacial rebound; and the distribution of deformation within tectonically active areas, such as western North America, the Pacific Basin, and the Alpine-Himalayan collision zone. Specific experiments should be selected through a peer-review process to ensure the highest quality of science.

- We recommend that resources be allocated among three modes of operation as follows: continuously recording arrays—45%; mobile campaigns (GPS / GLRS)—45%; Seafloor positioning campaigns—10%.

[3] We need globally coherent topography, geoid, and gravity coverage, and we need high-resolution satellite imagery and topography and gravity coverage in local areas.

These requirements are defined as:

- Global, coherent topographic data with moderately high accuracy (10 m vertical and 1 km horizontal). High resolution capability (a few meters vertical and 10 m horizontal) applied in selected areas.
- High resolution satellite images (roughly 1 m pixel size, even if only at single spectral band) for identification of structural, neotectonic and other morphologic features from space. Lower resolution (10 m) needed over a wide range of spectral bands to distinguish different lithologies.
- Globally dense, coherent gravity data to a few mgal at resolution of 50-100 km and local high-resolution gravity data to a few mgal at resolution approaching km.

[4] We require technological development to permit in a number of applications of space-based geodesy that are not possible with current capabilities.

Indispensable technology includes:

- a new generation of systems capable of continuous mm to sub-mm horizontal and vertical positioning on 1 to 1000 km vectors; systems capable of sub-cm relative positioning of moving platforms; and inexpensive (< \$10K), transportable (< 5 kg), and rugged instruments with minimal power requirements (~ 1 W);
- monumentation stable at the sub-millimeter level, and marks that can be installed rapidly and economically.
- seafloor mark positioning with a precision of better than 1 cm.
- more efficient and accurate processing techniques to reduce cost of analysis and delay in interpretation of large data sets;
- the creation and maintenance of a permanent geodetic archive for existing data sets and for those collected during the next decade, with common data formats and convenient access.
- effective, affordable, and practical means for exchange and dissemination of remote sensing data such as EosDIS or SESDIS. This effort should be coordinated with other agencies and countries.

5.2 A Global Fiducial Network

The most important recommendation of our panel is for the implementation of a world-wide space-geodetic fiducial network to provide a systematic and uniform measure of global strain. As outlined above, we recommend that this network consist of globally

distributed GPS receivers tied to a number of strategically located VLBI/SLR stations. We further recommend that some stations be equipped with an expanded set of additional sensors to facilitate calibration of various space-based data sets. These may include gravimeters, magnetometers, environmental sensors, and calibrated targets for various orbital instruments, such as those planned for Eos. In the long term, GLRS reflectors should be co-located with the VLBI/SLR and GPS stations.

Direct scientific benefits that will accrue from the proposed network include monitoring of :

- Plate motions, especially important for plates with poorly determined vector velocities;
- Short-term variations in rates of plate motion and deformation (days to years);
- Non-rigid behavior of plate interiors (important for models of plate driving forces);
- Rates of post-glacial rebound (constrains viscosity models for the mantle);
- Rates of sea-level change (crucial for study of global warming and climate change).

Additional benefits identified by our panel include:

- Determination of highly accurate orbits for GPS and other spacecraft;
- Mission support and satellite tracking;
- Calibration of globally coherent space-based topography, gravity and magnetic data;
- Calibration of a global set of GLRS reflectors;
- Establishment of an accurate fiducial network for local and regional space-geodesy;
- Assessment of natural hazards (earthquakes and volcanoes).

The specifications listed above for the number, density and type of space-positioning stations are based on both scientific and technical considerations: we require at least three sites per major plate to resolve rigid plate motions; mapping of non-rigid behavior within the interiors of plates requires a denser distribution. For example, with a station spacing of 1000 km there will be approximately 30 sites in North America - enough to map the distribution of non-rigid behavior across the continental part of the plate. The cost of deploying this number of VLBI or SLR stations would be prohibitive. GPS provides a relatively inexpensive alternative using current technology. The required accuracy of the network is dictated by the rates of movement that we wish to determine, as described in Table 1.

In tectonically active areas where deformation is concentrated, we need geodetic stations with intersite spacing much smaller than the 1000 km provided by the permanent sites within the network. We therefore recommend a vigorous long-term program of monitoring regionally dense space-geodetic networks through periodic campaigns (every two or three years) using portable equipment. These regional networks will be intimately tied to the permanent geodetic stations. Taken together, these two components —the permanent sites and the regional densification networks— will allow us to create a global strain map of the planet. Furthermore, the permanent fiducial network will foster studies of local and regional deformation because it will provide a means of tying local observations to a global framework and will greatly simplify the computations required to do so.

One of the outstanding problems with existing topography data is their lack of global coherence. Under our proposal, we will have 200 sites distributed around the world with accurately determined absolute elevations. This will permit topographic data sets to be calibrated precisely at each of these sites and removal of any offsets in the data sets. Similarly, enhancement of a subset of the global sites with other devices (e.g. gravimeters,

magnetometers, calibrated targets for orbital instruments) will provide superior calibration of a variety of other space-based observations of the Earth.

In addition to its obvious scientific benefits, the proposed network will facilitate the quest for natural hazard reduction by permitting study of the phenomena that control seismic and volcanic activity. Comparisons between crustal kinematics, seismicity and other environmental data are crucial to achieve a proposal understanding of these phenomena. Particularly noteworthy is the need to establish permanent geodetic, geophysical, and environmental facilities in areas of frequent volcanic or seismic activity, so as to acquire a continuous record of short-term behavior immediately before and after major eruptions and earthquakes and to aid in their prediction. Such facilities will also assist in the assessment of global warming through evaluation of absolute sea-level change and estimation of the rate of melting of polar ice-caps. Deployment of the proposed network in the 1990's will thus be timely in its response to the call for an increased emphasis over the next decade on the reduction of natural hazards and evaluation of man-made climate change.

Establishment and maintainance of a global network requires a long-term commitment and a global focus. While inter-agency and international participation is clearly critical to a successful deployment, it is imperative that a single agency take the initiative and the responsibility for the development and implementation. As a mission-oriented space agency with a global outlook, NASA is uniquely poised to lead this effort. As the prime developer of space geodesy, NASA is uniquely poised to tackle this technological challenge. Finally, NASA is perhaps the only agency in a position to make the necessary long-term commitment to this global program. In this light, we view deployment of a space-based geodetic network as an integral part of the *Mission to Planet Earth*.

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7. APPENDIX

- MEASUREMENT SYSTEMS -

The following space-dependent instrument systems are likely to contribute to plate motion and deformation studies during the next decade: Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Positioning System (GPS), Geoscience Laser Ranging System (GLRS), and Sub-Marine Positioning (SMP). This section highlights the aspects of these techniques that lend them most direct effectiveness.

7.1 VLBI, SLR

The key roles of VLBI/SLR in crustal deformation studies will be in supplementing other more flexible observing systems like GPS or GLRS. In particular, VLBI/SLR will play a critical role in maintaining a reference frame for GPS satellites, will provide independent observations for validation of longer range GPS or GLRS observations, and will provide boundary condition information for studies using GPS or GLRS to study local deformation.

During the next decade, it seems clear that the principal tool in investigating problems in crustal deformation will be the Global Positioning System (GPS). The principal applications of VLBI and SLR to regional and local deformation will be in several critical support roles: 1) maintaining a fiducial network tied to the center of mass of the Earth; 2) providing Earth orientation; 3) providing calibration and validation; and 4) providing boundary condition constraints. For many of the larger scale problems such as global plate motion the role of VLBI and SLR will be much more direct, but these are covered by other panel reports. At local and regional scales, GPS is a much more cost effective and flexible tool. Current results make it clear that for lines shorter than about 500 km GPS precision competes with VLBI.

One of the key roles of VLBI/SLR in crustal deformation studies will be in maintaining relative positions of a network of about 20 globally distributed sites. These sites must have collocated VLBI and SLR observations at least annually and continuous GPS observations. The position of these sites relative to each other and to the center of the Earth must be known and maintained at the 1 cm level. The position of the various antennas and marks within each site must be known and maintained at the 1 millimeter level. The necessity for these sites is discussed in the GPS section.

VLBI and SLR are the key components of the polar motion and UT1 series published by the International Earth Rotation Service (IERS). These series are an essential requirement for processing high precision GPS vectors.

A few vectors throughout the world should be chosen as collocation sites where VLBI and GPS observations are made simultaneously for the purposes of comparison of the two systems. Ideally these vectors would be about 500 km long: long enough for scale differences to be apparent, but short enough to be clearly in the useful range of GPS. All current studies indicate that the systems agree at the level of a few parts in 10^8 , but the current data is sparse and does not cover a very long time span. Vectors between the fiducial network stations will probably be too long for this purpose in general.

Last, but not least, VLBI and SLR must provide boundary condition information for use in interpreting the local and regional studies. This process is already occurring in the western coterminous U.S. and in Alaska, where global plate motion rates from VLBI supplement more detailed studies of the distribution of relative motion across the Pacific-North America boundary.

7.2 GPS

During the next decade, GPS will likely be the primary source of observational data for local deformation studies. The key challenge is to improve precision while making receivers more portable and easy to use and software less time-consuming. This will be even more challenging than it may appear because several forces are acting to degrade the precision. These forces are: potential military corruption of the signals; new receivers with less than full wavelength data on L₂; and mixtures of different antennas in experiments.

The advent of GPS has already caused a revolution in the measurement of crustal deformation. Prior to GPS, programs designed to systematically measure crustal deformation on a large scale were the exclusive province of government agencies both in the United States and in other countries. The availability of GPS has produced to a dramatic increase in the number of groups making these kinds of measurements. It is clear from several recent papers (Dong and Bock, 1989, Prescott et al., 1989, Tralli and Dixon, 1988) that under proper conditions GPS produces precision of a few mm on short lines and a few parts in 10⁸ on long lines. The "proper conditions" are an essential part of the demonstrated precision. All of the experiments obtaining high precision on vectors over 10 km in length have used extended observation sessions (5 to 9 hours of tracking per day and often several days of tracking at each site), dual band receivers with full wavelength data on both frequencies, and orbit improvement using data from tracking stations distributed over a continent-sized area. They have required person-months of processing time for each experiment. And the experiments have been carried out during the relatively quiet part of the solar cycle. It is not yet clear what precision will be obtained when these conditions are modified, and the conditions are being modified. Because of Department of Defense statements regarding access to GPS, most of the new receivers on the market do not provide full wavelength data on the second frequency. The sunspot number is increasing and with it the ionospheric activity. Fiducial stations necessary for orbit improvement do not exist yet except in a rudimentary and marginally useful form. During the next decade we must put effort into advancing GPS technology.

7.2.1 World-wide tracking network. We must develop a world-wide network of continuously tracking GPS receivers with relative position and velocities between sites determined by VLBI to the 1 cm and 1 cm/year level. At each site the relative positions should be maintained at the 1 mm level between the various instruments and through changes in instrumentation. Experience with existing prototype fiducial networks has made it clear that much work needs to be done to develop reliable receivers, software, and distribution mechanisms.

7.2.2 Development of new receivers. We need to continue to develop a next generation of field receivers which will be characterized by precise phase and pseudorange, low power consumption, compact size and light weight. There is also a need for a new generation of fixed-site receivers. These receivers need to operate reliably with minimal maintenance and operator attention, and produce very low noise pseudo-range and phase data. Issues such as weather resistance, power consumption, and weight are of less concern at fixed sites.

7.2.3 Validation of new receivers. There needs to be a methodical demonstration of the precision of new receivers and of the results when vectors are formed between different types of receivers. Current Federal Geodetic Control Committee testing is aimed more at a demonstration of functionality than at an exhaustive test. Networks will be observed with mixtures of receiver types or reobserved with different receivers than the original observations. We need to know what affect this will have on the results.

7.2.4 Algorithm development and improvement. Processing GPS data for high precision with today's receivers and software is very time consuming. Part of this time is the result of cycle slips and bad data with today's receivers and part of it is the result of the extent of human interaction required in selecting double difference combinations, lengths and number of parameters for orbit arcs, or fixing bias. The procedures used vary greatly from one processing system to another, but all systems require a great deal of time.

7.2.5 DoD cooperation. The civilian community should use all possible means to influence on the Department of Defense to make the system as useful as possible to the measurement of crustal deformation. The current broadcast orbits are precise enough to provide a starting orbit for preliminary processing with all vectors. For vectors less than about 10 km in length, the current broadcast orbits are precise enough for final processing. This is very convenient, and would allow implementation of near-real-time monitoring fairly conveniently. If these orbits are degraded significantly (e.g. under Selective Availability), we may need to think about replacing these orbits with some other near-real-time highly accessible source of orbits. Currently there are other sources of orbits (Naval Surface Weapon Center, Dahlgren, VA; University of Texas, Austin, TX; National Geodetic Survey, Rockville, MD) but they are available weeks after the observations. For some applications (monitoring volcanos and faults, post seismic studies, e.g. Japanese Tokai net) there is a need to operate GPS in real-time or near-real-time. The requirements of the geophysical community for high precision GPS are in the national interest whether the research is for hazard reduction or less directly applied. The Department of Defense must be made aware of our requirements.

7.2.6 Monumentation. Even with the current precision of GPS we are pushing the limits of the techniques used to tie the location of the observing instruments to a point on the ground. Better GPS can only aggravate this problem. We need investigations into the source of the signals seen in frequent high precision measurements (Langbein et al., 1987) and we need monumenting techniques to eliminate them if they are indeed noise.

7.2.7 Continuously operating GPS networks. In order to study the complete spectrum of geodetic signals, from periods of hours to decades, networks of continuously operating GPS receivers should be deployed in a few key areas. Using GPS, it is possible to obtain essentially continuous records of deformation. This will produce an entirely new geodetic data set. When combined with the records from shorter strainmeter-type instruments, these data will provide a powerful tool for investigating strain events such as pre- and post-earthquake deformation. These observations will provide data from a nearly unexplored part of the spatial and temporal deformation spectrum (period less than 1 week and scale greater than 1 km). With every new observation type there is an opportunity for quantum jump in our understanding.

7.3 GLRS

NASA is currently considering flying an altimetric and ranging laser on one of the polar Earth Observation System (EOS) platforms. GLRS will operate in two modes: a nadir-looking-altimetric-mode with a principal applications to ice sheet topography and cloud height; and a steerable ranging mode with a principal application in determining relative positions of ground sites. GLRS would greatly simplify the users side of positioning. The field sites would consist of corner cube reflectors with no requirements for on-site power, data processing capability, or data storage. GLRS will only begin to impact deformation studies during the next decade (it will be launched in 1996 or 1997). However, continued development of GLRS is essential to provide a complimentary system to existing GPS and ground-based geodetic techniques and to explore techniques for cheaper, easier and more precise measurements in the future.

7.4 SMP

Many important problems in crustal deformation will only be addressed when there exists a way of making precise observations to sub-marine points. Since two-thirds of the Earth's surface is water covered, it is not surprising that many areas of interest in deformation problems are wholly or partially under water. The percentage of plate boundaries that are sub-marine is even higher because of the non-random distribution of plate boundaries. Most plate boundaries occur either in the middle of the oceans or at the edges. There are relatively few plate boundaries that occur entirely on land.

These facts of geography suggest that the ability to position points on the bottom of the ocean would be a very useful in studying crustal deformation. Because of environmental factors, one can divide the problems and opportunities into three categories on the basis of distance: less than 1 km, 1-10 km, and greater than 10 km (Spiess, 1989). At distances shorter than 1 km, sub-aerial techniques can be adapted to use of the ocean bottom. Strainmeters and tiltmeters can be adapted to the oceanic environment, and visible light will propagate up to about a kilometer allowing ranging or angle measurements in a manner similar to land based observations. From 1 to 10 km it becomes necessary to use acoustic techniques. Knowledge of the effective speed of sound limits these techniques to about 1 part in 10^5 under the best conditions at present, with possible improvement to 1 part in 10^6 at best. Thus the range must be limited to 10 km in order to even approach 1 cm precision with purely acoustic techniques. Beyond 10 km, it is necessary to use composite systems with acoustic techniques locating a floating platform relative to the ocean bottom and space geodetic techniques, probably GPS, locating the platform relative to a distance mark, either another floating platform or a sub-aerial mark.

The current level of precision in the techniques, $\sigma = 10$ cm, suggests that it may be premature to consider widespread deployment, but the potential value of making measurements to sub-marine sites is great. Consequently, we recommend continuing a development effort in this technology with test applications until the precision reaches a level where the measurements can be expected to provide favorable signal-to-noise ratios with a few years of observations.

Table 2: Number of years required to detect tectonic motion as a function of the precision in the measuring system and the rate of motion. The motion is detectable when the change during the specified time period exceeds twice the standard deviation in the difference of the observations ($= 2\sqrt{2}\sigma$).

Tectonic rate	σ 10 cm	σ 1 cm
1 cm/yr	30 years	3 years
10 cm/yr	3 years	0.3 years

If the precision of sub-marine positioning is 10 cm/yr, it will be of value for measuring vectors between the fastest moving plates. As the precision increases the number of applications does also. We recommend continuing a development effort in this technology with only test applications until the precision reaches a level where the measurements can be expected to provide favorable signal-to-noise ratios in a few years.